CHAPTER 4

Transportation Costs

Drive thy business or it will drive thee.
—*Benjamin Franklin (1706–1790)*

INTRODUCTION

Good decisions at any step of the transportation project development process (PDP) require reliable information on the costs of alternative actions. Each stage of the PDP process involves costs (and benefits) to the agency, facility users, and the community. Certain benefits can be estimated in terms of reductions in user and community costs relative to a given base (typically, do-nothing) alternative.

Transportation costing generally involves estimation of the additional resources needed to increase the quantity or quality of the transportation supply from a given level, and analysts involved in transportation costing often encounter such concepts as economy of scale, price mechanisms, and demand and supply elasticities (McCarthy, 2001).

Typically, the first step in transportation system costing is to describe the physical systems involved and their operations (Wohl and Hendrickson, 1984). The required factors of production (including material, labor, and equipment input), are then identified and their costs determined. Alternatively, an aggregate approach that uses data from several similar past projects can be used to develop average unit costs per facility dimension, usage, or demand. The cost functions and average values presented in this chapter are mostly useful for purposes of sketch planning. For bidding purposes, it is more appropriate to develop precise cost estimates using data from detailed site investigations, engineering designs, and planned policies and operational characteristics of the system.

In this chapter we first present classification systems of the costs encountered in different modes of transportation. Then the components of agency and user costs are discussed and alternative ways of estimating these costs are presented. We also show how costs can be adjusted to account for differences in implementation time periods, location, and project size (economies of scale). Finally, contemporary costing issues such as cost overruns and vulnerability and risk costs are discussed.

4.1 CLASSIFICATION OF TRANSPORTATION COSTS

Transportation costs may be classified by the source of cost incurrence, the nature of variation with the output, the expression of unit cost, and the point in the facility life cycle at which the cost is incurred.

4.1.1 Classification by the Incurring Party

Transportation costs may be classified by the source of cost incurrence. *Agency costs* are the costs incurred by the transportation facility or service provider; *user costs* are the monetary and nonmonetary costs incurred by the transportation consumers, such as passengers, commuters, shippers, and truckers. Section 4.2 provides a detailed discussion of agency costs. *Community* or *nonuser costs* represent the costs incurred by the community as a whole, including entities not directly involved with use of the facility and are often referred to as secondary costs or *externalities*. Community costs can be nonmonetary (such as disruption of community cohesiveness) or monetary (such as a change in property values). Figure 4.1 shows the various costs categorized by incurring party.

4.1.2 Classification by the Nature of Cost Variation with Output

The costs of transportation systems typically comprise a fixed component, which is relatively insensitive to output volume, and a variable component, which is influenced by output volume, and can be expressed as follows:

$$\text{total cost, TC}(V) = k + f(V)$$

where k is the fixed-cost component (FC), $f(V)$ is the variable-cost component, and V is the output volume.

Agency capital costs can be expressed in terms of the size or number of capacity-enhancing features made available by the proposed project (e.g., the number of lane-miles, line-miles, transit buses or trains); the fixed-cost component comprises the costs of acquiring the right-of-way and relocating or replacing structures and utilities; and the variable-cost component involves cost elements to support the increased operation (e.g., driver and fuel costs for urban bus systems). Agency operating costs are

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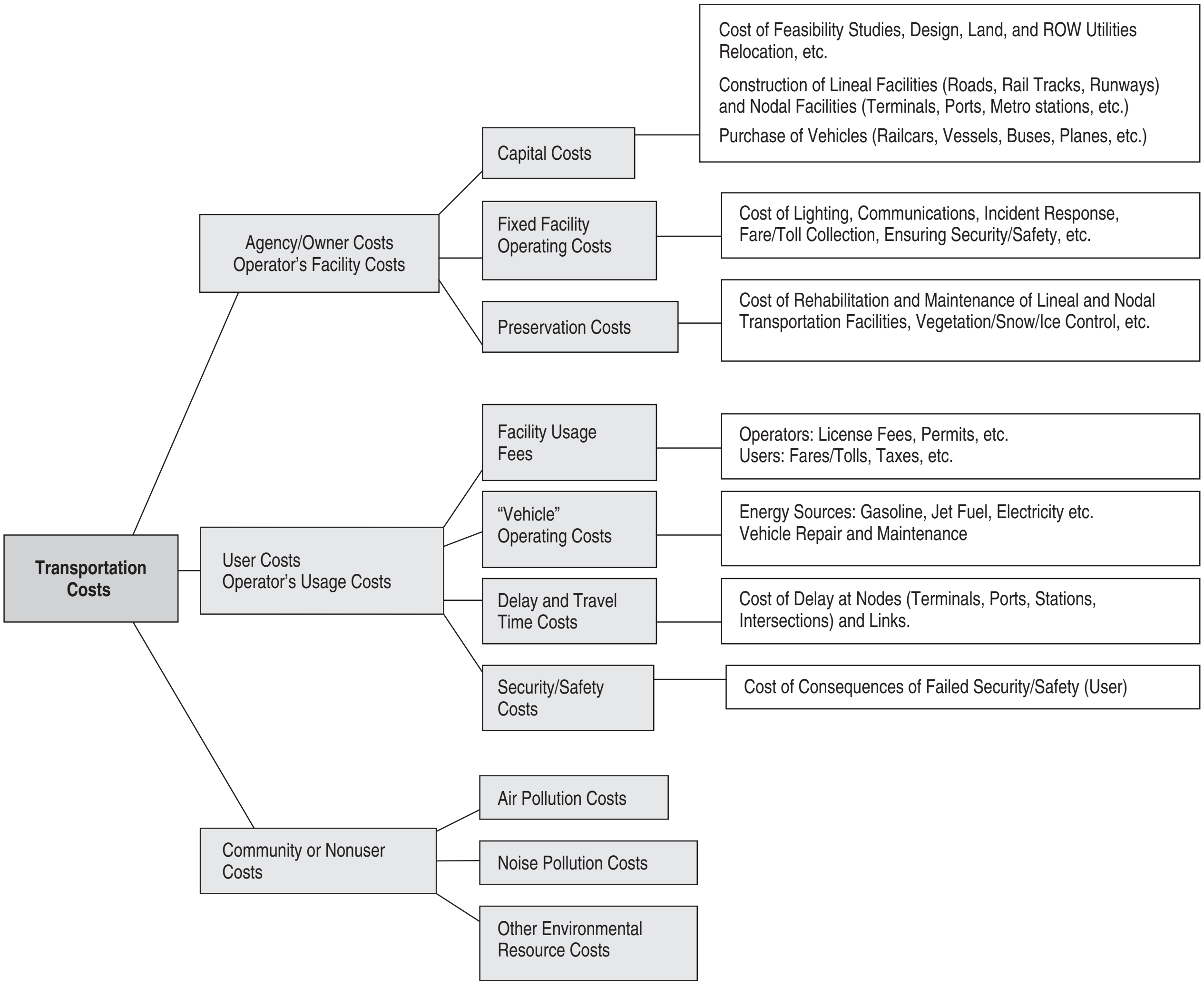

Figure 4.1 Transportation costs categorized by source of cost incurrence.

often more applicable to vehicles using the facility than of the facility itself, which therefore makes these costs a major issue in evaluating transit improvements.

A transportation cost function's mathematical form and the relative magnitudes of its fixed and variable components (variable–fixed cost ratio), and the current output level are all expected to indicate whether or not a transportation system will exhibit scale economies. The variable–fixed cost ratio is in turn influenced by the work scope (construction vs. preservation), the facility dimensions, and the incurring party (facility owner, shipper, or auto user). The ratio is generally low for construction and high for maintenance, low for transportation modes owned and operated by the same entity (such as rail and pipeline transportation), and high for modes where the owner of the fixed asset and the user/operator are separate entities, such as air, water, and truck transportation. In the last case, the relatively small fixed costs incurred by the operator are those associated with the purchase or lease of vehicles (planes, ships, and trucks) and fixed fees associated with facility use, while the large variable costs arise from fuel use, vehicle maintenance, labor costs, and so on.

4.1.3 Classification by the Expression of Unit Cost

(*a*) *Average Cost* The average total cost, ATC, is the total cost associated with 1 unit of output. It is calculated as the ratio of the total cost to the output: $\text{ATC} = \text{TC}/V$, where TC is the total cost and V is the volume (output). The average fixed cost, AFC, is the fixed cost associated with 1 unit of output and is calculated as the ratio of the fixed cost to the output, $\text{AFC} = \text{FC}/V$. Similarly, the average variable cost is the cost of 1 unit of output and is calculated as the ratio of the variable cost to the output, $\text{AVC} = \text{VC}/V$. The concept of average costs is useful in the economic evaluation of transportation system improvements because it helps assess the cost impacts of improvements at a given supply level.

(*b*) *Marginal Cost* The marginal cost of a transportation good or service is the incremental cost of producing an additional unit of output. The terms of incremental cost, differential cost, and marginal cost have essentially similar meaning but typically are used in contexts that have very subtle differences (Thuesen and Fabrycky, 1964). *Incremental cost* is a small increase in cost. *Differential cost* is the ratio of a small increment of cost to a small increase in production output. Marginal cost analysis is relevant in transportation system evaluation because an agency may seek the incremental cost changes in response to planned or hypothetical production of an additional unit of output with respect to facility construction, preservation, or operations. Marginal cost and average cost can differ significantly. For example, suppose that an agency spends \$10 million to build a 10-mile highway and \$10.5 million to build a similar 11-mile highway, the average costs are \$1 million and \$0.954 million, respectively, but the marginal cost of the additional mile is \$0.5 million. The expressions related to marginal cost are as follows:

Marginal variable cost:

$$\text{MVC} = \frac{\partial \text{VC}}{\partial V}$$

Marginal total cost:

$$\text{MTC} = \frac{\partial \text{TC}}{\partial V} = \frac{\partial \text{FC}}{\partial V} + \frac{\partial \text{VC}}{\partial V} = \frac{\partial \text{VC}}{\partial V} = \text{MVC}$$

Like average cost, marginal cost concepts help an agency or shipper to evaluate the cost impacts of various levels of output or the additional cost impact of moving from a certain output level to another.

Example 4.1 A cost function is expressed in the following general form: total cost (TC) $= k + f(V)$, where k is the fixed cost (FC) and $f(V)$ is the variable cost. V is the output. For each of the functional forms shown in Table E4.1 derive expressions for (a) average fixed cost, (b) average variable cost, (c) average total cost, (d) marginal variable cost, and (e) marginal total cost.

SOLUTION The expressions are shown in Table E4.1.

Example 4.2 The costs of running a metropolitan bus transit system are provided in Table E4.2. Plot the graphs of (a) total cost, variable cost, and fixed costs; (b) average total costs, average variable costs, and average fixed costs; and (c) marginal total costs and average total cost. Show the point at which marginal total cost equals average total cost, and explain the significance of that point.

SOLUTION The graphs are shown in Figure E4.2. The region on the left of the intersection point (MC < AC) represents scale economies and the region on the right represents scale diseconomies (MC > AC). An agency would prefer to produce goods or provide services in the region where MC < AC. Since revenue is a linear function

Table E4.1 Typical Cost Functions and Expressions for Unit Costs

	$\text{TC} = k + aV$ (Linear)	$\text{TC} = k + aV^2$ (Quadratic)	$\text{TC} = k + ae^V$ (Exponential)	$\text{TC} = k + aV^3$ (Cubic)	$\text{TC} = k + a \ln V$ (Logarithmic)	$\text{TC} = k + ab^V$ (Power)
Average fixed cost = FC/V	k/V	k/V	k/V	k/V	k/V	k/V
Average variable cost = $\text{VC}(V)/V$	a	aV	ae^V/V	aV^2	$(a \log V)/V$	ab^V/V
Average total cost = $\text{TC}(V)/V$	$k/V + a$	$k/V + aV$	$k/V + ae^V/V$	$k/V + aV^2$	$k/V + a \times \log V/V$	$k/V + ab^V/V$
Marginal variable cost = marginal total cost	a	$2aV$	ae^V	$3aV^2$	a/V	$a \ln(b) b^V$

Table E4.2 Transit Agency's Costs

	Annual Ridership (V) in millions							
	1	2	3	4	5	6	7	8
Fixed cost, FC	3	3	3	3	3	3	3	3
Variable cost, VC	1.250	1.375	1.500	1.625	1.750	1.875	2.000	2.125
Total cost, TC	4.250	4.375	4.500	4.625	4.750	4.875	5.000	5.125
Average fixed cost, AFC	0.300	0.150	0.100	0.075	0.060	0.050	0.043	0.038
Average variable cost, AVC	0.125	0.069	0.050	0.041	0.035	0.031	0.029	0.027
Average total cost, AC	0.425	0.219	0.150	0.116	0.095	0.081	0.071	0.064
Marginal variable cost, MVC	—	0.125	0.125	0.125	0.125	0.125	0.125	0.125
Marginal total cost, MC	—	0.125	0.125	0.125	0.125	0.125	0.125	0.125

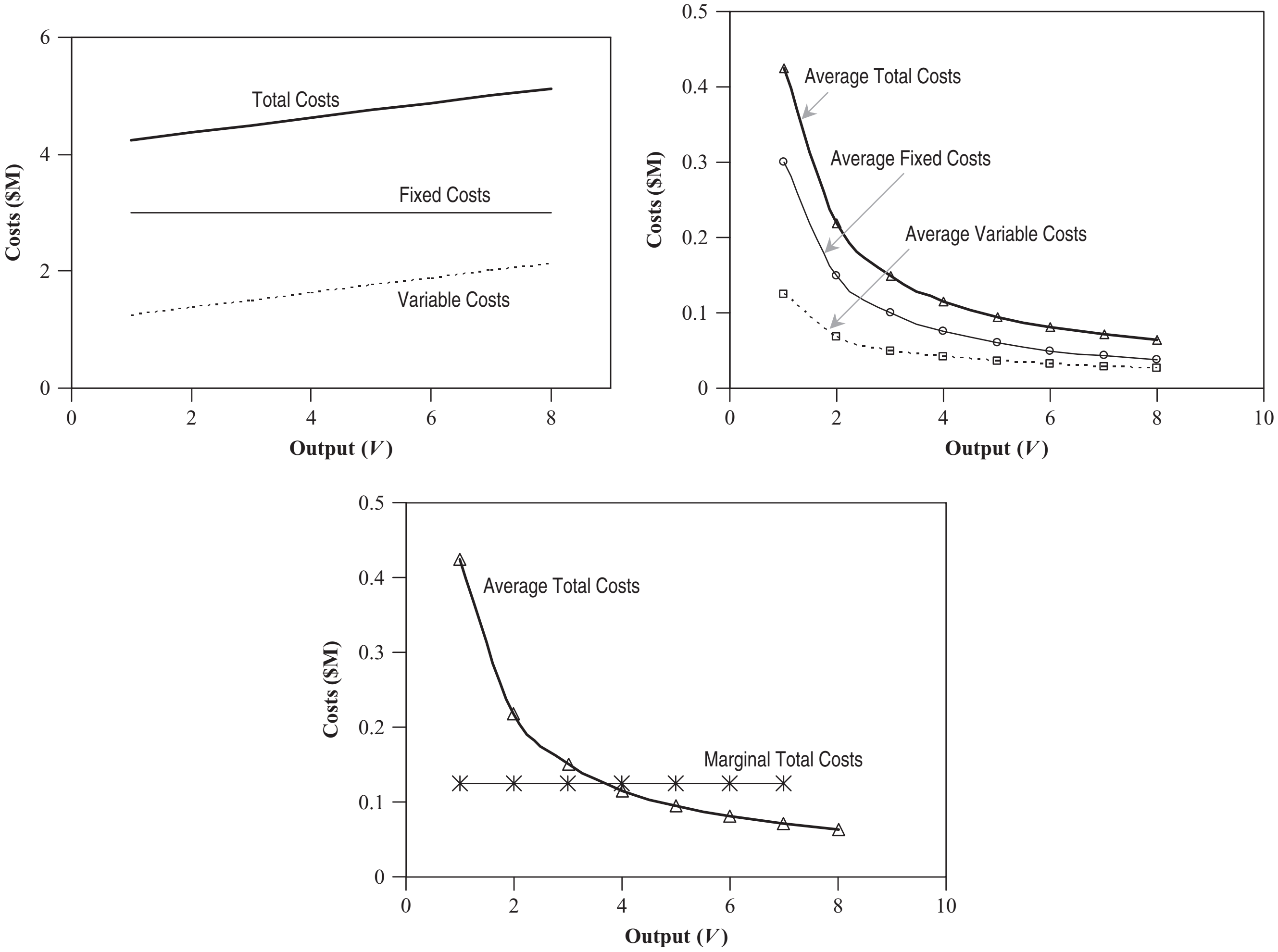

Figure E4.2 Marginal, average, fixed, and variable cost relationships.

of ridership ($R = aV$), transit agencies are interested in knowing maximum ridership that can be achieved while ensuring that MC is less than or equal to AC. The maximum level of ridership corresponds to the intersection point between the average total cost and the marginal total cost (at that point, revenue is maximized). The generated revenue will most likely not cover the costs incurred by the transit agency. It should be kept in mind, however, that unlike private entities, the primary goal of public agencies is to provide service rather than to maximize profit. As such, for many transit agencies, maximum revenue is less than agency cost and therefore such agencies often operate on subsidies.

Example 4.3 The cost function associated with air shipping operations of a logistics company is Total Cost (in \$ millions) $= 1.2 + 150V^2$, where V is the monthly output (volume of goods delivered) in millions of tons. Plot a graph showing the average total cost and marginal total cost.

SOLUTION

The average total cost function is

$$\mathrm{AC} = \frac{V}{\mathrm{TC}} = \frac{1.2}{V} + 150\mathrm{V}$$

The marginal total cost function is

$$\mathrm{MC} = \frac{\partial \mathrm{TC}}{\partial V} = 300V$$

Plots of these functions are provided in Figure E4.3

(*c*) *General Discussion of the Average and Marginal Cost Concepts* In this section we presented the concepts of average and marginal effects from a monetary cost perspective. In some transportation problems, the analyst may need to apply these concepts to the consumption of nonmonetary resources (e.g. environmental degradation, community disruption) as well as system benefits (e.g., system preservation, congestion mitigation, safety improvement, air quality enhancement).

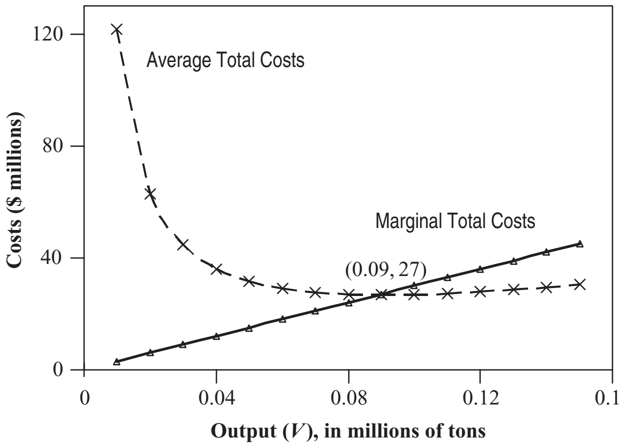

Figure E4.3 Average and marginal cost relationships.

Another issue is the selection of the appropriate output, V, to be used in the cost analysis. This depends on the transportation mode and the phase of the transportation development process in question. For example, in aggregate costing of rail transit construction, the number of stations and length of the system can be used as output variables. In aggregate costing of rail or airport operations, the number of passenger miles or passenger trips could be used. In the case of highway operations, the traffic volume or vehicle miles of travel could be used. In freight operations costing, ton miles or ton trips could be used.

4.1.4 Classification by Position in the Facility Life Cycle

Life-cycle costs include relevant agency and user costs that occur throughout the life of a transportation asset, including the initial costs. In general, transportation costs over its life cycle may be classified as *initial costs* and as *subsequent costs.* The latter are incurred at later stages of facility life and therefore involve activities such as operations, preservation of the fixed asset or rolling stock, and costs that are associated with salvage or disposal of the physical facility or rolling stock.

4.1.5 Other Classifications of Transportation Costs

Transportation agency costs may also be categorized according to the source of work (activities carried out by an agency's in-house personnel vs. activities let out on contract), the role of the work (activities aimed at preventing deterioration vs. activities geared toward correcting existing defects), or the cycle over which costs are incurred (activities carried out routinely vs. activities carried out at recurrent or periodic intervals).

4.2 TRANSPORTATION AGENCY COSTS

Agency costs refer to the expenditures incurred by the facility owner or operator in providing the transportation service. For fixed assets, agency costs are typically placed into seven major categories: advance planning, preliminary engineering, final design, right-of-way acquisition and preparation, construction, operations, preservation, and maintenance. In some cases, disposal of the fixed asset at the end of its service life involves some costs that are referred to as *salvage costs.* For movable assets (rolling stock), agency costs typically comprise acquisition, vehicle operating preservation, maintenance, and disposal costs.

4.2.1 Agency Costs over the Facility Life Cycle

Several types of agency costs are incurred over the life of a transportation facility. However, not all of these costs may be applicable in a particular evaluation exercise. The analyst must identify the costs that do not vary by transportation alternative and must exclude these costs from the evaluation. Typically, the initial agency costs of planning and preliminary engineering are the same across alternatives. Also, where facility locations have already been decided, location-related expenses, such as right-of-way (ROW) acquisition and preparation, are fixed across alternatives. Furthermore, where it is sought to only evaluate alternative construction practices, preservation strategies, or operational policies, the cost of design can be excluded from the evaluation.

(*a*) *Advance Planning* These may include the cost of route and location studies, traffic surveys, environmental impact assessments, and public hearings. Advance planning costs are typically estimated as a lump sum based on the price of labor-hours within the transportation agency or from selected consultants. In evaluating alternatives, costs should exclude any costs of advance planning work done prior to development of the alternatives.

(*b*) *Preliminary Engineering* These may include the costs of carrying out an engineering study of a project, such as geodetic and geotechnical investigations. If some preliminary engineering has been done (especially regarding technical feasibility of competing alternatives), such costs may be excluded from project costs.

(*c*) *Final Design* These are the costs of preparing engineering plans, working drawings, technical specifications, and other bid documents for the selected design. Final design costs typically are 10 to 20% of construction costs.

(*d*) *Right-of-Way Acquisition and Preparation* Acquisition costs of ROW land typically include the purchase price, legal costs, title acquisition, and administrative costs of negotiation, condemnation, and settlement. Severance damages are typically significant, and determining the value of remnant acquisitions is often a complex task. In the absence of other information, fees and charges associated with ROW acquisition may be assumed to be 2% of the purchase price. Right-of-way preparation costs include relocation or demolition of structures and utility relocation. A preliminary estimate of the costs for acquiring and preparing ROW costs can be made by a quick field inventory of the project alignment to determine the volume of structures slated for demolition, and applying the agency's demolition cost rates. For structures that need to be relocated, it is necessary to consider the costs of acquiring new land and reconstructing such structures. The basis for residential relocation payments, including costs of temporary rentals, may be established by existing policy of the transportation agency or government. The relocation cost of existing utility facilities, such as water, gas, telephone, and electricity should be estimated with the assistance of utility companies.

(*e*) *Construction* At the planning stages, rough approximations of construction cost can be made on the basis of similar past projects. To do this, it may be useful to employ statistical regression to develop such costs as a function of work attributes, location, and so on. Alternatively, the cost may be built up using unit costs of individual constituent work items. Such estimation of transportation project construction costs may seem a relatively easy task but may be complicated by lack of estimating expertise (Dickey and Miller, 1984), a problem that has often led to cost discrepancies in transportation project contracts.

(*f*) *Operations* These costs may include charges for utility use (e.g., electricity for transit or air terminals, street lighting, and traffic signal systems), safety patrols, traffic surveillance and control centers, ITS initiatives, toll collection, communication equipment, labor, and so on. Given adequate historical data, it may be possible to develop annual operating cost models for estimating future operating costs. Such models are typically a function of facility type and size, age of facility, and level of use.

(*g*) *Preservation and Maintenance* These are the costs incurred by an agency to ensure that an asset is kept in acceptable physical condition. For a highway agency, for instance, preservation costs include pavement and bridge rehabilitation as well as preventive and routine maintenance, vegetation control, and snow and ice control. Predictions of preservation maintenance costs may be made in the form of simple average cost rates (such as cost per line-mile of rail track or cost per square meter of bridge deck) or statistical models that estimate facility cost as a function of facility dimensions, material type, and other factors.

4.2.2 Techniques for Estimating Agency Costs

Costing of transportation projects and services can generally be carried out in two alternative ways: a disaggregate approach and an aggregate approach. Further details and examples of each approach are provided here.

(*a*) *Disaggregate Approach* (*Costing Using the Prices of Individual Pay Items or Treatments*) In this approach, the overall cost of an entire project is estimated using the *engineer's estimate* or the contractor's *bid prices* for each specific constituent work activity (also referred to as a *pay item*) of the project. Pay items may be priced in dollars per length, area, or volume, or weight of finished product, and is often reported separately for materials, labor and supervision, and equipment use. This method of costing is more appropriate for projects that have passed the design stage and for which specific quantities of individual pay items are known. It is generally not appropriate for projects whose design details are not yet known.

The use of detailed pay item unit costs for estimating the cost of transportation facilities or services is straightforward but laborious. For a project, there can be several hundreds, sometimes thousands, of pay items that are priced separately. This costing approach typically forms the basis for contract bidding. The first step is the decomposition of a specific work activity (such as rail track installation) into constituent pay items expressed in terms of finished products (such as one linear foot of finished rail guideway) or in terms of specific quantities of material (such as aggregates, concrete, steel beams, formwork), equipment, and labor needed to produce one linear foot of finished guideway. After the various components of the work activity have been identified, a unit price is assigned to them (on the basis of updated historical contract averages or using the engineer's estimates), and the total cost of the work activity is determined by summing up the costs of its constituent pay items. The level of detail of the pay items generally depends on the stage of the transportation project development process at which the cost estimate is being prepared. At the early planning stages, relatively little is known about the prospective design; therefore, the level of identifying the pay items and their costing is quite coarse (Wohl and Hendrickson, 1984). Cost estimators typically refer to four distinct levels of coarseness that reflect the stages at which such estimates are typically required:

1. Conceptual estimate in the planning stage (typically referred to as *predesign estimate* or *approximate estimate*)
2. Preliminary estimate in the design stage (often termed *budget estimate* or *definitive estimate*)
3. Detailed estimate for the final assessment of costs
4. As-built cost estimate that incorporates any cost overruns or underruns

In its coarser form, cost accounting utilizes more aggregated estimates that are for groups of pay items rather than for individual pay items. Average cost values may be used, but a more reliable method would be to develop cost models as a function of facility attributes such as material type, construction type, size, surface or subsurface conditions, and geographical region. There may be other variables, depending on whether the costs being estimated are initial construction costs or whether they are costs incurred over the remaining life of the facility. The time-related variables (such as accumulated environmental and traffic effects) have little or no influence on initial construction cost but significantly affect subsequent costs (i.e., preservation and maintenance costs).

At another level of disaggregation, average cost values and cost models can be developed for each *treatment* (a specific agency activity) that is comprised of multiple pay items or for each pay item.

(*b*) *Aggregate Approach* (*Costing*) An example of this approach is a model that estimates the overall cost associated with the construction, preservation, or operations per facility output or dimension. In a manner similar to the disaggregate approach, costs developed using the aggregate approach can be in one of two forms:

1. An average rate, where historical costs for each system family are updated to current dollars, averaged, and expressed as a dollar amount per unit output (dimension). *Family* refers to a number of systems placed in one group on the basis of similar characteristics. For example, the estimated average cost of rigid pavement maintenance was determined to be \$480/lane-mile per annum (Labi and Sinha, 2003). Average rates may be developed for each subcategory: for example, rigid interstate pavements located in a certain region or certain types of rigid pavements (plain, reinforced, continuously reinforced, etc.).

2. A statistical model, where historical overall costs are modeled as a function of facility characteristics (e.g., facility dimensions, material, construction type, age).

An example of an aggregate cost model (for a heavy rail transit system) is as follows:

$$\text{Unit Cost} = 3.9 \times L^{-0.702} \times U^{1.08} \times ST^{-0.36}$$

where Unit Cost = cost per line-mile-station in \$M
L = number of line-model
U = fraction of the system that is underground
ST = number of stations

Also, statistical models can be developed for each subcategory, or differences in subcategories could be included in a broad model as dummy variables. Costs developed using the aggregate approach are typically used for sketch planning and long-range budgeting where the application of specific treatments (and thus their corresponding individual costs) are not known with certainty and only rough approximations of overall costs are sought.

4.2.3 Risk as an Element of Agency Cost

(*a*) *Risk due to Uncertainties in Estimation* Most cost models that are currently used by transportation agencies treat input variables as deterministic values that do not adequately reflect the uncertainty that actually exists in the real world. Such uncertainty is introduced by factors such as fluctuations in work quality, material and labor prices, climate, etc. (Hastak and Baim, 2001). Risk analysis may be used to address the issue of uncertainty. Risk analysis in transportation costing answers three basic questions about risk (Palisade Corporation, 1997): What are the possible outcomes of cost? What is the probability of each outcome? What are the consequences of decisions based on knowledge of the probability of each outcome? Values of input variables that influence transportation costs are modeled using an appropriate probability distribution that is deemed by the analyst to best fit the data for each variable. Then the expected overall cost outcome is determined. This can be repeated, using Monte Carlo simulation, for several values of the variable within the probability distribution defined.

(*b*) *Risk due to Disasters* Risk-based transportation costing also involves natural and human-made disasters that can significantly influence the operations and physical structure (and consequently, the costs of physical preservation and operations of such facilities). Natural disasters include floods, earthquakes, and scour, human-made disasters include terrorist attacks and accidental collisions that critically damage transportation infrastructure. The probability of a transportation system failure can be assessed for each vulnerability type. Then the cost of damage or repair in that event can be used to derive a failure cost or vulnerability cost that could be included in the transportation system costing (Chang and Shinozuka, 1996; Hawk, 2003). Vulnerability cost can be defined as follows:

$$\text{vulnerability cost} = \text{probability of disaster occurrence}$$
$$\times \text{ cost of damage if the disaster occurs.}$$

Risks are evident in both the probability of the occurrence and the uncertainties of damage cost in the event of disaster. As evidenced from the 2005 Katrina hurricane disaster on the U.S. Gulf coast, estimating the damage cost can be as uncertain as estimating the probability of the event itself.

4.3 TRANSPORTATION USER COSTS

4.3.1 User Cost Categories

User impacts that can be monetized include vehicle operating costs, travel-time costs, and safety costs. Nonuser or community costs (e.g., of air pollution, noise, water pollution, community disruption) are not so easily monetized. Both user and community costs are often related directly to the physical condition as well as the performance of a facility. For example, excessive congestion and poor physical condition of rail lines can translate to high user costs of safety and delay, and high community costs due to noise.

(*a*) *Travel-Time Costs* Travel time is one of the major items in the evaluation of alternative transportation systems. The cost of travel time is calculated as the product of the amount of travel time and the value of travel time. Methods for assessing the amount and value of travel time (in minutes, hours, etc.) and its monetary value ($ per hour, etc.) are discussed in Chapter 5.

(*b*) *Safety Costs* The costs of safety can be estimated as either preemptive costs or after-the-fact costs. Preemptive safety costs are incurred mostly by the agency in ensuring that crashes are minimized and may be considered as agency operating costs; after-the-fact safety costs are those incurred by users (through fatality, injury, or vehicle damage), the agency (through damaged facilities such as bridge railings or guardrails), or the community (through damage to abutting property, pedestrian casualties, for example). In Chapter 6 we present unit crash costs and a methodology to estimate safety costs and incremental safety benefits of transportation projects.

(*c*) *Vehicle Operating Costs* Irrespective of mode, the costs of operating transportation vehicles can be substantial. In Chapter 7 we provide details on VOC components and factors, unit values of VOC, and the methodology for evaluating the impact of transportation system improvements on the operating costs of transportation vehicles.

(*d*) *Noise, Air, and Water Pollution Costs* Noise, air, and water pollution costs can be estimated in terms of preemptive costs or after-the-fact costs. In any case, there seems to be no universally adopted method of valuation of these effects. Consequently, they are typically not included in economic efficiency analysis of transportation projects but are instead considered in cost-effectiveness framework without monetization.

4.3.2 Impacts of Demand Elasticity, Induced Demand, and Other Exogenous Changes on User Costs

When a transportation system is improved (through enhanced service or physical condition, the resulting decrease in user costs causes a shift of the supply function to the right. This decrease constitutes the user benefits. There are three possible scenarios for which such user benefits can be estimated (Dickey and Miller, 1984): when demand is inelastic, when demand is elastic and there are induced trips, and when demand is elastic and there are generated trips.

The foregoing discussion is presented for a composite user cost but is also applicable to individual user cost types. In some cases where detailed data are unavailable, the analysis of user costs may be simplified by using an overall value for user costs rather than summing up values of individual components of user costs. For each situation, the change in user costs can be calculated using simple geometry: area of a rectangle for Figure 4.2 and area of a trapezoid for Figures 4.3 and 4.4.

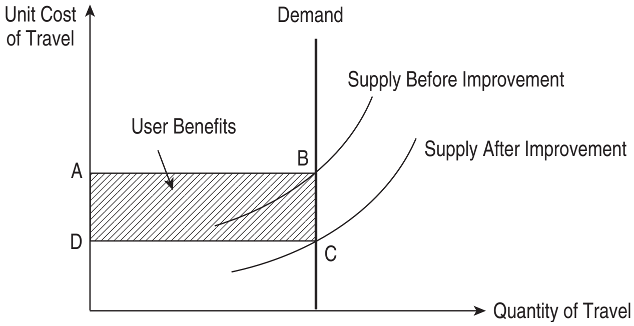

Figure 4.2 Unit user cost when demand is perfectly inelastic.

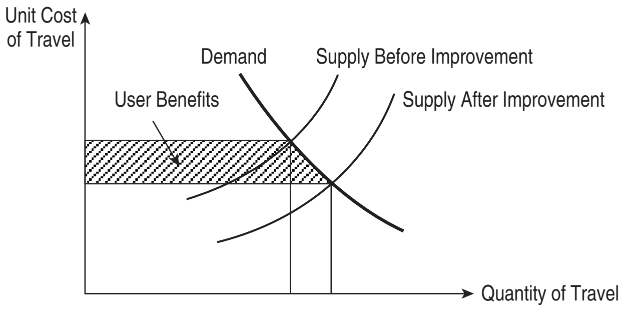

Figure 4.3 Unit user cost when demand is elastic and there are induced trips.

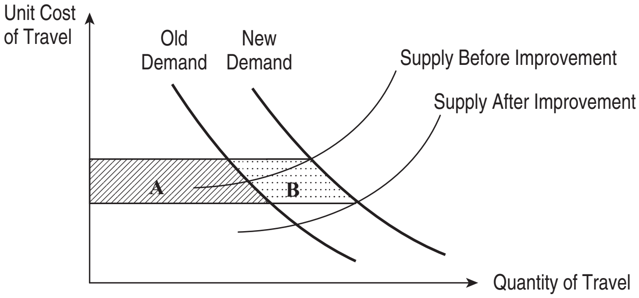

Figure 4.4 Unit user cost when demand is elastic and there are trips generated.

(*a*) *When Demand Is Inelastic* When demand is inelastic (therefore precluding any induced, generated, or diverted trips), the user benefit occurring from an improved transportation system is taken as the product of the reduction in the unit cost (price) of travel and the number (quantity) of trips (Figure 4.2). For purposes of illustration, a *travel unit* will be taken as a trip. For example, a technological improvement such as electronic tolling that decreases delay and hence reduces the unit cost of each trip would generally cause a downward shift in the supply curve, leading to user benefits. On the contrary, a new transportation policy such as security checks that increases delay (and hence the unit cost of each trip) is reflected by an vertical upward shift in the supply curve (and equilibrium point) indicating negative user benefits in the short run, all other factors remaining the same. In both cases, the number of trips would remain the same because demand is inelastic.

(*b*) *When Demand Is Elastic and There Are Induced Trips* When demand is elastic, an increase in supply, from classical economic theory, results in lower user cost of transportation and subsequently, increased or induced demand. Thus, the area (shown in Figure 4.3 as user benefits) is trapezoidal in shape and is greater than the rectangular area that corresponds to the product of the unit price reduction and the number of trips. For example, improved transit service through higher service frequency and increased reliability would decrease the user cost of delay. This can be represented by a downward right shift of the supply curve and equilibrium point, all other factors remaining the same. The number of trips and user benefits would increase. On the other hand, an intervention that increases fares would increase the cost of travel, all other factors remaining the same, and would be reflected by an upward left shift of the supply curve and equilibrium point. The number of trips would decrease and the user benefits of such an intervention would be negative.

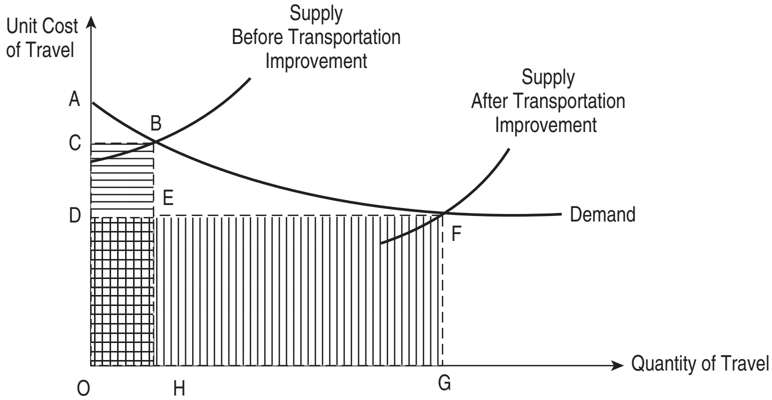

Figure 4.5 Change in total user costs.

(*c*) *When Demand Is Elastic and Trips Are Generated* When demand is elastic and there is a shift in the demand curve (due to increased demand even at the same price), the increase in user benefits (consists of Areas A and B in Figure 4.4) but Area B is due only in part from the improvement. The changes in user benefits for the scenarios discussed above are in response to changes within the transportation system itself, such as nature of demand elasticity, changes in demand (induced or generated), or changes in supply (trip delays, travel times, price). The figures can also help explain the effect of *exogenous changes*, which include:

- Change in prices of VOC components
- Implementation or removal of user subsidies or taxes
- Technological advancements in areas outside (but related to) the transportation system in question

A case in point is the 2005 increase in gasoline prices in the United States. This generally caused an increase in the unit cost of each personal or business trip in the short run. Users with elastic demand reduced their trips, while those with inelastic demand had the same number of trips after the change. In either case, the end result was a negative gain in user benefits. Another example is the user subsidization that typically occurs in some developing countries. When transportation users are subsidized by the government, this lowers the supply curve because the unit cost of each trip is reduced. This leads to increased travel (where demand is elastic) and increased benefits (for either elastic or inelastic demand). The removal of subsidies or the imposition of taxes has the opposite effect.

Transportation projects and services are typically implemented with the objective of lowering congestion, increasing safety, and decreasing travel time—such reductions in user costs translate into increases in quality of life, business productivity, retention and attraction of investments, increased employment, and so on. However, an increase in transportation supply does not always lead to a decrease in total travel costs. Depending on the shape of the demand and supply functions and the elasticity of demand, a decrease in unit travel costs could lead to a decrease or increase in total user costs (Dickey and Miller, 1984). For example, Figure 4.5 shows that (1) the benefits of the transportation system improvement (the area DCBF) are not necessarily equal to the change in total user costs (the area ODFG − the area OCBH), and (2) the total user costs in this scenario actually increases with the decrease in unit travel costs due to the system improvement (the area represented by rectangle ODFG is much larger than that represented by rectangle OCBH).

4.4 GENERAL STRUCTURE AND BEHAVIOR OF COST FUNCTIONS

A cost function is a mathematical description of the variation of cost with respect to some output variable (typically system dimensions or the level of system use). There are three major aspects of transportation cost functions: the *dependent variable, independent variables* (including the *output dimension*), and the *functional form* of the cost function.

4.4.1 Components of a Transportation Cost Function

(*a*) *Dependent Variable* This is typically the cost of the output, in monetary terms and in a given time period. To adjust for the effects of inflation it is often necessary to express the cost items in constant dollar. For facility construction and improvement projects, construction price indices are used to convert current dollars to constant dollars, as discussed in Section 4.6.2. Generally, the dependent variable can be a total cost or a unit cost (total cost per unit output). In using the unit cost as the dependent variable, the analyst typically calculates unit costs for each observation (e.g., cost per lane-mile per passenger-mile), or per ton-mile and then develops statistical functions of such costs with respect to output, facility dimensions and/or other characteristics. This approach presupposes that costs are linearly related to the output variable, thus impairing investigation of scale economies. A superior and more flexible approach is to use the total cost as the dependent variable and to use the output variables, among other variables, as the independent variable. Then using calculus, the elasticities of the response variable with respect to each independent variable can be determined, and then the existence and extent of scale economies or diseconomies can be identified.

(*b*) *Independent Variables* Two types of factors affect cost levels: (1) those related to the output, such as number or frequency of trains or buses, number of trips, tons of material shipped, passenger-miles, vehicle-miles, or ton-miles (these are referred to as *output variables*) and (2) those independent of output, such as spatial location. Output-related variables typically constitute the variable component of a cost function, while the nonoutput variables typically comprise the fixed component. Examples of output variables typically used in cost functions or rates for capital costs of physical transportation infrastructure are shown in Table 4.1.

(*c*) *Functional Form* Nonlinear functional forms, which include quadratic, cubic, exponential, logarithmic, and power forms, are generally more appropriate than linear forms, as they are capable of accounting for scale economies or diseconomies.

4.4.2 Economies and Diseconomies of Scale

Economy of scale refers to the reduction in average cost per unit increase in output; *diseconomy of scale* refers to the increase in average cost per unit increase in output. Through operational efficiencies (or inefficiencies) or by virtue of inherent features of the facility or its environment, the cost of producing each additional unit may rise or fall as production increases. For a given cost function,

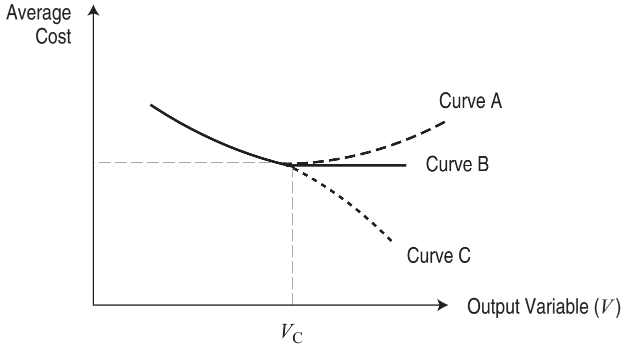

Figure 4.6 Variations of average cost reflecting scale economies and diseconomies.

Table 4.1 Possible Variables for Agency Cost Functions or Rates

	Physical Infrastructure	Operations
Highways	Pavements: cost per lane-mile of new pavement, cost per volume of laid/cast material Bridges: cost per area of new or rehabilitated bridge (measured using deck area)	Congestion/mobility: cost per travel-time reduction, cost per unit resource for incident management Safety: cost per unit reduction in fatal and injury crashes
Bus and rail transit	Cost per bus or railcar, cost per route-mile	Cost per passenger, cost per passenger-mile, cost per revenue vehicle
Rail freight	Track: cost per line-mile Terminals: cost per terminal, cost per floor area (of terminals) Yards: cost per yard area	Cost per passenger, cost per enplanement
Air travel	Cost per area of passenger terminal, cost per runway length, cost per runway area	Cost per ton load of freight, cost per passenger
Marine ports	Cost per area of facility, cost per dock	Cost per passenger-mile, Cost per freight ton-mile

scale economies or diseconomies with respect to any output variable are typically represented by the index of that variable in the cost equation and can be investigated by plotting observed total or average unit cost vs. the output variable (Figure 4.6). Depending on facility type and level of output, the average cost at a certain output level, V_C, may increase (curve A) or decrease (curve C) or may remain the same (curve B).

4.5 HISTORICAL COST VALUES AND MODELS FOR HIGHWAY TRANSPORTATION SYSTEMS

4.5.1 Highway Agency Cost Models

(*a*) *Cost Models by Improvement Type* A widely used set of project costs are those developed as part of the Highway Economic Requirements System (Table 4.2). Efforts have been carried out in individual state, provincial, and local highway agencies to derive average costs of capital improvement project types. Wilmot and Cheng (2003) for instance, developed a model to estimate future overall highway construction costs in Louisiana in terms of resource costs (construction labor, materials, and equipment), contract characteristics, and the environment. Also, Labi and Sinha (2003) established average costs for standard pavement preservation treatments and capital improvements in Indiana.

The amounts shown in Table 4.2 are average values, and the cost of a specific project may be less or more than the amount shown, due to such factors as:

- *Number of crossings and ramps* (*i.e., over water, railway, other highway*). Highway projects with higher numbers of crossings require more bridges, leading to higher overall costs per mile.
- *Right-of-way*. A project that is built within an existing right-of-way has lower unit costs than one that needs additional right-of-way.
- *Environmental impacts*. Projects in environmentally sensitive areas generally have higher unit costs.
- *Existing soil and site conditions*. High variability in soil conditions can translate to higher unit costs.
- *Project size*. Larger projects generally have lower unit costs due to scale economies. For some facilities, however, the need for additional stabilizing structures beyond certain facility dimensions may translate into a greater cost increase per unit increase in dimension, thus reflecting scale diseconomies.
- *Project complexity*. More complex projects typically have higher unit costs.
- *Method of construction delivery*. Projects constructed using traditional contracting processes generally have lower unit costs than those for projects constructed using alternative processes such as design–build and warranties. It is worth noting, however, that facilities constructed using traditional contracting processes may have higher unit preservation costs over their life cycle.
- *Urban or rural location*. Urban projects generally have higher unit costs than those of their rural counterparts.

Other factors that may affect project costs include the degree of competition for the contract, design standards, labor costs, material and workmanship specifications, and topographic and geotechnical conditions. For the foregoing reasons, comparing or transferring states' construction costs using bid price data should be done with extreme caution. Factors that cause large cost differences should be identified, and unit prices from such contracts may be excluded from the comparison.

(*b*) *Cost Models for Pay Items and Factors of Production* A number of state transportation agencies, such as California, Massachusetts, Arizona, Indiana, Texas, and Arkansas, publish their historical transportation construction and maintenance cost data online. In some cases, these data include the prices of individual pay items of the winning bid as well as those of the engineer's estimate. At a national level, pay item data are available through AASHTO's *Trns.prt Estimator*, an interactive Windows-based stand-alone cost estimation system for highway construction. For analysts who are interested in the prices of raw materials, labor, materials, and equipment use, the Federal Highway and Transit Administrations' Web sites, have useful data that track trends in prices. This database is made possible through continual reporting to the FHWA and FTA, cost data from the states that cover key work items and materials. The FHWA publishes bid price data in its quarterly *Price Trends for Federal-Aid Highway Construction* and in its annual *Highway Statistics* series.

4.5.2 Transit Cost Values and Models

Transit agency costs include (1) capital cost items such as land acquisition, construction of tracks (guideways), stations, and ancillary facilities; (2) vehicle (rolling stock) costs, and (3) operating costs. Factors affecting rail transit costs include system length, number of stations, vertical alignment, and fraction of the system underground. Also, it is usually more expensive to build a rail rapid transit line than a bus rapid transit line, partly because rail lines require additional and more expensive facilities, such as power supply, signals, and a safety control system. In a tunnel, however, it may be less expensive to build a rail line because rail cars are smaller than buses,

Table 4.2 Highway Improvement Costs (Thousands of 2005 Dollars per Lane-Mile)

Functional Class	Terrain	Reconstruct and Add High-Cost Lanes	Reconstruct and Add Normal-Cost Lanes	Reconstruct and Widen Lanes	Reconstruct	Major Widening at High Cost	Major Widening at Normal Cost	Minor Widening	Resurface and Improve Shoulders	Resurface
Rural interstate	Flat	759	759	855	713	477	477	386	265	150
	Rolling	888	888	944	734	509	509	415	280	144
	Mountainous	1,023	1,023	1,251	1,042	670	670	570	343	185
Rural other principal arterial	Flat	957	957	729	623	490	490	378	184	94
	Rolling	990	990	820	704	547	547	416	200	94
	Mountainous	1,409	1,409	1,074	880	1,020	1,020	593	273	137
Rural minor arterial	Flat	831	831	562	443	483	483	314	185	79
	Rolling	904	904	707	604	668	668	329	188	84
	Mountainous	1,223	1,223	1,103	791	847	847	435	234	132
Rural major collector	Flat	732	732	641	454	460	460	253	129	45
	Rolling	802	802	776	562	457	457	267	141	52
	Mountainous	1,073	1,073	993	774	781	781	355	181	65
Urban sections	Freeways and expressways	11,227	4,828	3,541	2,169	11,396	4,996	2,102	628	292
	Other divided	6,677	2,667	2,181	1,236	7,139	3,130	1,159	430	196
	Other undivided	4,716	1,724	1,896	1,130	5,327	2,335	1,227	375	222

Source: Costs have been indexed from 1997 dollars shown in the HERS Technical Report Version 3.26, December 2000. The improvement costs in this table include right-of-way.

thus requiring smaller tunnels, and do not emit exhaust gases, whose removal requires special tunnel ventilation facilities (Black, 1995). The various transit types, which are illustrated in Figure 4.7, are defined as follows (TRB, 2003; APTA, 2005):

- *High-speed rail:* a commuter railway primarily for intercity travel. There are several high-speed facilities in Europe and Asia, and recently, a Maglev high-speed transit facility has been constructed in Shanghai, China, to connect the city center and the main airport. Figure 4.8 provides a summary of unit construction cost for high-speed rail.
- *Heavy rail:* an electric railway with the capacity for a heavy volume of traffic, operating on an exclusive right-of-way that is separate from all other vehicular and pedestrian traffic. Heavy rail is often characterized by high-speed and rapid-acceleration movements, and its passenger railcars operate individually or in multicar trains on fixed rails.
- *Commuter rail:* an electric- or diesel-propelled variation of heavy rail purposely for urban passenger train service, consisting of local short-distance travel operating between a central city and adjacent suburbs. Because of its service characteristics, it is sometimes referred to as *metropolitan rail, regional rail*, or *suburban rail*.
- *Light rail:* lightweight passenger rails system that operates with one- or two-car trains on fixed rails. Unlike heavy-rail service, light rail operates on nonexclusive right-of-way that is mostly not separated from other traffic. Also known as *streetcars, trams*, or *trolley cars*, light-rail vehicles are often operated electrically.

(a) (b)

(c) (d)

Figure 4.7 Major categories of rail transit and bus transit: (*a*) heavy (rapid) rail (photo courtesy of Doug Bowman, Creative Commons Attribution 2.0 license); (*b*) commuter rail (photo courtesy of LERK, Creative Commons Attribution 2.5 license); (*c*) light rail; (*d*) bus rapid transit (photo courtesy of Shirley de Jong, Creative Commons Attribution ShareAlike 2.5 license).

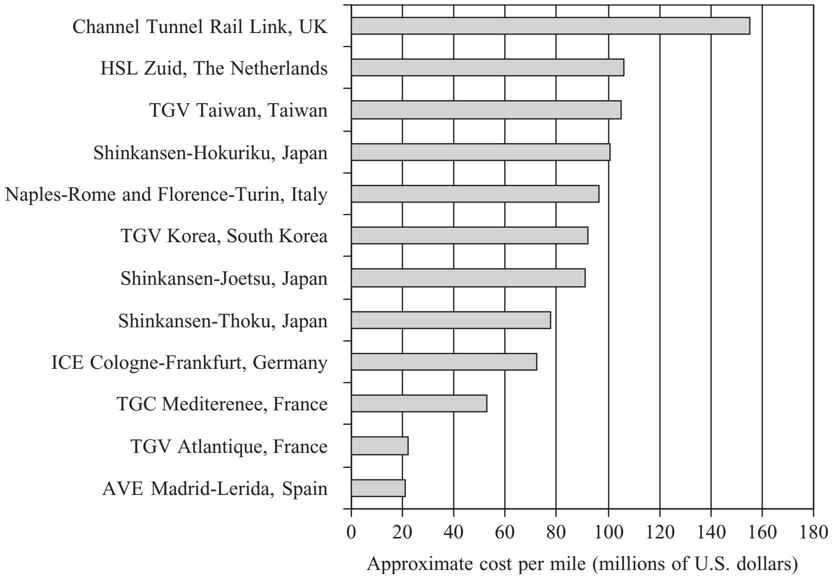

Figure 4.8 Costs of high-speed rail in Europe and Japan. (Adapted from CIT, 2004.)

- *Monorail:* a railway system that uses cars running on a single rail. Typically, the rail is run overhead and the cars are either suspended from it or run above it. Driving power is transmitted from the cars to the track by means of wheels that rotate horizontally, making contact with the rail between its upper and lower flanges.
- *Bus rapid transit:* essentially, a rubber-tired version of light-rail transit with greater operational flexibility. It can include a wide range of facilities, from mixed traffic and curb bus lanes on streets to exclusive busways.
- *Bus transit:* traditional urban bus transit, mostly using city streets.

(*a*) *High-Speed-Rail Capital Costs* As shown in Figure 4.8, the cost of high-speed rail construction varies from country to country. This is due to variations in availability and prices of factors of production such as land and labor. In the United States, Acela Express high-speed trains operate between Washington, DC and Boston via New York City and Philadelphia along the northeast corridor of the United States.

(*b*) *Heavy* (*Rapid*)-*Rail Capital Costs* On the basis of historical data, the total cost of heavy-rail construction can be decomposed by subsystem as follows (Cambridge Systematics et al., 1992): land, 6%; guideway, 26%; stations, 26%; trackwork, 4%; power, 3%; control, 5%; facilities, 2%; engineering and management/testing, 15%; and vehicles, 13%.

Like high-speed rail, heavy-rail systems typically involve a large capital outlay. For example, the 104-mile 43-station San Francisco Bay Area Rapid Transit, most of which was completed in 1974, cost approximately $3.82 billion in 2005 dollars. In the late 1980s, the cost of building a heavy-rail line was approximately $100 to $300 million per line-mile (in 2005 dollars), depending on the number of stations and the fraction of system constructed underground (Table 4.3). The table shows the capital costs of heavy (rapid)-rail transit systems constructed at four major cities in the United States.

A rough model for estimating the unit cost of heavy (rapid)-rail construction is as follows: For heavy (rapid)-rail systems with 40 to 60% underground, the average cost is $14.4 million per line-mile-station, and the cost model is

$$\begin{aligned} \mathrm{UC} &= 3.906 \times \mathrm{LM}^{-0.702} \times \mathrm{PU}^{1.076} \\ &\quad \times \mathrm{ST}^{-0.358} \qquad R^2 = 0.94 \end{aligned} \tag{4.1}$$

where UC is the unit cost (cost per line-mile-station), in millions of 2005 dollars, LM the number of line-miles, PU the percentage of system underground, and ST the number of stations. Therefore, given basic information such as the expected system length (miles), average number of lines, number of stations, and surface–underground fraction, the expected overall cost of a heavy (rapid)-rail system can be roughly estimated.

For example, the estimated cost of a two-station 10-lane-mile heavy-rail system with 50% underground is

Table 4.3 Capital Costs of Selected Heavy (Rapid)-Rail Transit Systems

	City	Line-Miles	Percent Underground	Number of Stations	Capital Cost (millions of 2005 dollars)	Cost per Line-Mile (millions of 2005 dollars)	Cost per Line-Mile-Station (millions of 2005 dollars)
Partially underground	Atlanta	26.8	42	26	4,693	175	6.74
	Baltimore	7.6	56	9	2,224	293	32.52
	Washington	60.5	57	57	13,749	227	3.99
Fully above ground	Miami	21	0	20	2,314	110	5.51

Source: Adapted from Cambridge Systematics et al. (1992).

$(3.906)(10)^{-0.702}(50)^{1.076}(2)^{-0.358} = \$40.74$ million per line-mile-station. Also, the cost of a similar 10-station 50-lane-mile system with 50% underground is $(3.906)(50)^{-0.702}(50)^{1.076}(10)^{-0.358} = \$7.40$ million per line-mile-station. Equation (4.1) shows the existence of economies of scale in heavy (rapid)-rail construction costs; the higher the number of stations or line-miles, the lower the cost per station or per line-mile.

Example 4.4 Eighty-five percent of a proposed heavy-rail transit system in the city of Townsville will be located aboveground. The total length is 12 line-miles; four stations are planned. Determine the estimated project cost.

SOLUTION The cost per line-mile-station $= (3.906)(12^{-0.702})(15^{1.076})(4^{-0.358}) = 7.66$. Therefore, the overall cost of the system is $(7.66)(12)(4) = \$367.68$ million.

While Table 4.3 presents detailed useful information such as the number of line-miles, stations, and the percentage underground, its data are aggregated for all segments of a given city's heavy (metro)-rail systems. On the other hand, Table 4.4 presents the unit construction cost of various segments in each city but does not show details by number of stations, line-miles, and the underground fraction.

(*c*) *Capital Costs of Light-Rail Fixed Facilities* The capital costs of light-rail transit systems vary considerably by construction type. There are generally about six different types of light-rail construction, classified by the extent and manner in which the guideway is buried in the ground. *At-grade structures* are grounded on the surrounding terrain. *Elevated light-rail structures* are installed on columns so that they are above the surrounding terrain. *Fill structures* are constructed on an embankment on the existing ground. *Subway light rails* are those located completely below ground. On the basis of the data from light-rail systems in Portland, Sacramento, San Jose, Pittsburgh, and Los Angeles, the distribution of total light-rail construction costs are as follows: guideway elements, 23%; yards and shops, 5%; systems, 10%; stations, 5%; vehicles, 13%; special conditions, 7%; right-of-way, 8%; and soft costs, 29%. *Special conditions* refer mostly to utility relocation; *soft costs* include demolitions, roadway changes, and environmental treatment (Booz Allen Hamilton, 1991). Table 4.5 presents the unit cost of various light-rail projects in the United States.

Table 4.4 Metro-Rail Construction Cost per Mile

Heavy (Metro)-Rail Project	Cost per Mile (millions of 2005 dollars)
Atlanta MARTA	
Phase A	248.0
Phase B	117.2
Phase C	120.5
Baltimore Metro	
Sections A and B	123.0
Section C	357.5
Los Angeles Red Line	
Segment 1	697.8
Segment 2	349.6
Segment 3a	333.3
Washington Metro	
Orange Line	232.5
Red and Blue Lines	203.5
Green Line, Blue Extension	310.7
Average cost per mile	281.2

Source: Adapted from Parsons Brinckerhoff (1996).

Table 4.5 Light-Rail Construction Cost per Mile

Light-Rail Project	Cost per Mile (millions of 2005 dollars)
Baltimore Central Line	18.8
Phase 1	
Three extensions	16.4
Dallas DART S&W Oak Cliff	31.3
Park Lane	58.6
Denver RTD	24.4
Central Corridor	
Southwest Extension	20.3
Los Angeles MTA	43.4
Blue Line	
Green Line	49
Portland Tri-Met	26.6
Banfield	
Westside	56.7
Sacramento RTD	12.4
Original Line	
Mather Field Road Extension	15.4
Salt Lake City UTA South Line	21.4
St. Louis MetroLink Phase 1	20.8
San Diego Trolley	31.3
Blue Line	
Orange Line	23.5
Santa Clara County VTA	26.2
Guadalupe Corridor	
Tasman Corridor	43.8
Average cost per mile	36.6

Source: Adapted from U.S. General Accounting Office (2001).

Guideways for Light Rail: Guideway construction typically accounts for 16 to 38% of overall capital costs (Black, 1995). Of the various light-rail construction types, subway guideway construction is by far the most costly, followed by retained-cut guideway systems. Guideways on at-grade levels and elevated fills are the least expensive types of light-rail construction. Table 4.6 presents the capital costs per line-mile (expressed in 2005 dollars) for light-rail guideways constructed at various urban areas in the United States. The average cost is $36.6 million per mile, in 2005 dollars.

For estimating the approximate guideway cost of a light-rail project whose construction type is known, the average cost values shown in the last column of Table 4.6 may be used. However, at the initial planning stage, the type of light-rail construction may not be known. In such cases, the analyst may provide a rough estimation of the project capital costs using the following model, developed using data from 22 U.S. cities where light-rail projects were implemented in the 1992–2005 period (Light Rail Central, 2002):

$$\begin{aligned}\text{Total guideway cost} &\\ &= \exp(-1997.92 + 1448.22\ \text{LENGTH}^{0.0005}\\ &\quad + 553.55\ \text{STATIONS}^{0.0005}) \qquad R^2 = 0.61 \qquad (4.2)\end{aligned}$$

where the total guideway cost is in millions of 2005 dollars, LENGTH is the system length in miles, and STATIONS is the number of stations.

Example 4.5 It is proposed to construct a 20-mile light-rail system in the city of Megapolis. The number of stations is not yet known. Given the nature of the terrain, an elevated fill structure is recommended. Determine the estimated cost of the guideway for the system. If the guideway is expected to account for 30% of the capital cost of the overall system, estimate the total capital cost of the project.

SOLUTION Using the average cost for elevated fill structure from Table 4.6, estimated guideway cost $= (5.87)(20) =$ \$117.4 million; total system cost $= (117.40)(100/30) =$ \$391.33 million.

Example 4.6 A new light-rail system planned for a rapidly growing city will be 21 miles in length and will serve 13 stations. The construction type has not yet been decided. Find the total and average (per mile-station) guideway cost of the system. An alternative being considered is to construct the system to cover 38 miles and to serve 22 stations. Find the average guideway cost of the second alternative, and explain for any differences in average guideway costs between the two alternatives.

SOLUTION Using equation (4.2),

$$\begin{aligned}\text{Total cost for alternative 1} &\\ &= \exp[-1997.92 + (1448.22)(21^{0.0005})\\ &\quad + (553.55)(13^{0.0005})] = \$868.35 \text{ million}\end{aligned}$$

$$\begin{aligned}\text{Average cost} &= \frac{\$868.35}{(21)(13)}\\ &= \$3.18 \text{ million per mile-station}\end{aligned}$$

$$\begin{aligned}\text{Total cost for alternative 2} &\\ &= \exp[-1997.92 + (1448.22)(38^{0.0005})\\ &\quad + (553.55)(22^{0.0005})] = \$1544.71 \text{ million}\end{aligned}$$

Table 4.6 Guideway Cost for Selected Light-Rail Construction Types

	Guideway Cost[a] (millions of 2005 dollars)					
Type of Guideway Construction	Portland	Sacramento	San Jose	Pittsburgh	Los Angeles	Average Cost (per mile)
At-grade	10.74	3.68	5.43	4.10	5.67	5.93
Elevated structure	27.11	3.65		5.67	26.62	15.76
Elevated retained, fill		9.60		8.56	8.41	8.91
Elevated fill				6.23	5.49	5.87
Subway			61.39	64.02	61.82	62.41
Retained cut		44.33	2.36	43.71	27.93	29.58

Source: Adapted from Booz Allen Hamilton (1991).

[a] Design, engineering, right-of-way acquisition, and other administrative costs are excluded.

$$\text{Average cost} = \frac{\$1544.71}{(38)(22)}$$
$$= \$1.84 \text{ million per mile-station}$$

Alternative 2 represents a 42% reduction in average cost. This can be attributed to economy-of-scale effects.

Stations and Yards for Light Rail: Construction of passenger stations and rolling stock maintenance yards often constitutes a significant fraction of overall transit capital costs. Table 4.7(a) presents the unit capital costs of light-rail passenger stations in five cities of the United States, expressed in 2005 dollars. It can be seen that stations for subway station construction are by far the most costly, followed by those for elevated guideway systems.

Table 4.7(b) presents the capital costs of light-rail transit yards and mechanical shops in 2005 dollars. The costs do not include design, engineering, right-of-way acquisition, and other administrative costs. The average cost for the construction of rail transit yards and shops was $600,000 per unit of capacity. *Capacity* represents the maximum number of vehicles that can be held in the maintenance yard.

Example 4.7 It is proposed to construct 20 passenger stations for a planned subway light-rail system. A maintenance yard and shop with a capacity of 60 vehicles is also proposed. Estimate the overall capital cost for stations and yards for the project.

SOLUTION

Average cost of passenger station for subway light-rail transit system = $26,982,000

Cost of 20 passenger stations

= (20)($26,982,000) = $539,640,000

Average cost of maintenance yard

= $600,000 per unit capacity

Cost of 60 capacity units

= (60)($600,000) = $36,000,000

Total capital cost for stations and yards

= $575,640,000

(*d*) *Capital Costs of Monorail Fixed Facilities* Table 4.8 presents the cost of monorail construction per mile. The average cost is approximately $220 million per mile. This includes the cost of the guideway, stations, and other ancillary structures.

(*e*) *Rolling Stock Capital Costs for the Various Rail Transit Types* Table 4.9 presents the unit costs of rolling stock for various rail transit system types. Estimated costs for both heavy- and light-rail vehicles exceed $2 million each, expressed in 2005 dollars. Table 4.10 shows the unit costs of rehabilitating rolling stock in 2005 dollars.

Example 4.8 A transit agency wishes to purchase 55 new cars for its heavy-rail system. Also, it is expected that rehabilitation of these cars will be carried out twice in their life cycle. What is the estimated total capital cost of the new fleet over their life cycle?

SOLUTION From Table 4.9, average purchase cost per car = $2.3 million. Purchase cost of 55 cars = (55)($2.3 million) = $126.5 million. From Table 4.10, average rehabilitation cost per car = $0.84 million. Total rehabilitation

Table 4.7 Light-Rail Transit Capital Costs at Selected Locations

(a) Passenger Station Costs per Station (thousands of 2005 dollars)

Type of Construction	Portland	Sacramento	San Jose	Pittsburgh	Los Angeles	Average
At-grade center platform	831		263		1,656	917
At-grade side platform	910	636	312	3,248	1,401	1,302
Elevated					4,493	4,493
Subway				11,491	42,473	26,982

(b) Maintenance Yards and Shops

Location	Yard and Shop Capital Costs (thousands of 2005 dollars)	Yard and Shop Capacity (vehicles)	Cost per Unit of Capacity (thousands of 2005 dollars)
Portland	22,549	100	226
Sacramento	6,900	50	138
San Jose	31,846	50	637
Pittsburgh	72,323	97	746
Los Angeles	67,817	54	1,256
Average			600

Source: Adapted from Booz Allen Hamilton (1991).

Table 4.8 Monorail Construction Cost per Mile

Monorail Project	Cost per Mile (millions of 2005 dollars)
Las Vegas Extension (planned)	197.6
Newark Airport mini-monorail	274.8
Kitakyushu monorail	179.3
Average cost per mile	217.2

Source: Adapted from Parsons Brinckerhoff (2001), LTK Engineering Services (1999).

cost of 55 cars = (55)($0.84 million)(2) = $92.4 million. Therefore, the estimated total capital cost = $218.9million.

(*f*) *Bus Rapid Transit Capital Costs* BRT facility development costs depend on the location, type, and complexity of construction. The costs of existing systems were reported to be $7.5 million per mile for independent at-grade busways, $6.6 million per mile for arterial busways located in the road median, and $1 million for mixed traffic and/or curb bus lanes (TRB, 2003). The costs can be many times higher when tunnels and other features for exclusive guideways are included. Table 4.11 shows the costs (in U.S. dollars) of selected bus rapid transit systems at locations around the world.

(*g*) *Rail Transit Operating Costs* Rail transit operating costs consist of salaries, wages, and fringe benefits; utilities (power supplies); and maintenance of rolling stocks, stations, and rail tracks (guideways), while bus transit operating costs include salaries, wages, and fringe benefits; fuel; and vehicle and terminal maintenance. Operating costs may be reported in two ways:

1. As a function of supply-based measures; in other words, operating cost may be expressed as a function of inventory size, system type, or some physical attribute of the system. Examples include operating cost per mile, per vehicle, and per expected vehicle-miles of travel. Note that for rail transit where schedules are not always a reliable indicator of the level of ridership, VMT (unlike passenger-miles of travel) may not be a reliable measure of consumed service demand. Operating cost functions are useful at the facility planning stage where a cost estimate is sought for operating the system.
2. As a function of demand-based measures; in other words, operating cost may be expressed as a function of operating cost per passenger, per vehicle, per passenger-hour, per passenger-mile, and so on. These types of operating cost models are more useful for performance

Table 4.9 Unit Rolling Stock Costs for Various Rail Transit System Types

Type of system	Location	Year	Quantity Ordered	Cost for Total Order[a]	Cost per Car[a]	Average Cost per Car[a]
Heavy (rapid)-rail transit	Chicago	1991	256	350.49	1.37	2.3
	Los Angeles	1989	54	106.70	1.98	
	New York	1990	19	66.35	3.49	
	San Francisco	1989	150	385.44	2.57	
	Washington, DC	1989	68	140.64	2.08	
Light-rail transit	Boston	1991	86	222.86	2.58	2.6
	San Diego	1991	75	205.97	2.75	
	St. Louis	1990	31	76.65	2.46	
Commuter rail	Florida	1990	6	9.96	1.65	2.4
	Los Angeles	1990	40	86.10	2.16	
	New Jersey	1991	50	76.31	1.52	
	New York	1990	39	153.64	3.93	
	Indiana	1991	17	46.43	2.74	

Source: Adapted from Cambridge Systematics et al. (1992).

[a] In millions of 2005 dollars adjusted from actual dollars as of order date. Variations in unit costs are due to type of vehicle, size of order, and options.

Table 4.10 Costs of Rolling Stock Rehabilitation

Type of System	Location	Year	Car Type	Quantity Rehabilitated	Cost for Total Order[a]	Rehabilitation Cost per Car[a]	Average Rehabilitation Cost per Car[a]
Heavy (rapid) rail transit	New York	1991	R33 subway	494	339.35	0.69	0.84
	New York	1991	R44 subway	280	250.54	0.89	
	New York	1990	R44 subway	64	60.78	0.95	
Commuter rail	Maryland	1990		35	11.82	0.34	0.99
	New Jersey	1991		230	376.66	1.64	

Source: Adapted from Cambridge Systematics et al. (1992).

[a] In millions of 2005 dollars adjusted from actual dollars as of 1991. Variations in unit costs are due to type of vehicle, size of order, and options.

assessments than they are for cost estimation of future projects. However, if the future demand is known, these types of operating cost functions can be used to derive operating cost estimates for purposes of future project planning.

Table 4.12 presents average operating costs for various transit modes, in terms of four cost related performance measures. These costs have not been corrected for possible scale economies. Data are for all heavy and light rail systems in the United States and the 20 largest bus systems in terms of average weekday passengers. It is seen that bus transit, as compared to other modes, has lower operating cost per vehicle-hour and per vehicle-mile, slightly higher cost in terms of passenger-mile, and similar costs per passenger-trip. Heavy rail has the lowest operating cost per passenger-mile, followed by light rail. This could be because rail transit cars are larger than those of bus transit, and people tend to make longer trips on rail than on buses. As such, the unit operating costs of rail systems enjoy higher economies of scale than bus transit in terms of passenger-miles. Operating

Table 4.11 Cost of Development for Selected BRT Systems

Facility	Location	Miles	Cost (millions of 2005 dollars)	Cost/Mile (millions of 2005 dollars)	Notes
Bus tunnels	Boston—Silver Line	4.1	1477.09	359.97	Includes bus lanes
	Seattle	2.1	492.36	234.15	
Busway	Hartford	9.6	109.41	10.94	
	Houston—HOV system	98	1072.26	21.88	
	Los Angeles—San Bernardino Freeway	12	82.06	6.56	
	Miami	8.2	64.55	7.66	
	Ottawa	37	320.58	8.75	
	Pittsburgh—South Busway	4.3	29.54	6.56	
	East Busway	6.8	142.24	20.79	
	West Busway	5	300.89	60.18	
	Adelaide (guided bus)	7.4	57.99	7.66	
	Brisbane[a]	10.5	218.83	20.79	
	Liverpool—Parramatta	19	109.41	5.47	
	Runcorn	14	16.41	1.09	
Freeway, reversible	New York—I-495 New Jersey	2.5	0.77	0.33	
Reversible lanes	I-495 New York	2.2	0.11	0.11	
	I-278 Gowanus	5	10.94	2.19	Involves freeway reconstruction
Arterial street median busways	Cleveland	7	240.71	31.73	
	Eugene	4	14.22	3.50	
	Bogota	23.6	201.32	8.75	
	Quito	10	63.02	6.56	
	Belo Horizonte			1.75	
Mixed Traffic–curb bus lanes	Los Angeles	42	9.08	0.22	
	Vancouver—Broadway	11	9.85	1.09	
	Richmond	9.8	48.14	4.49	
	Leeds (guided bus)	2.1	5.47	2.63	
	Rouen (optically guided bus)	28.6	218.83	7.66	

Source: Adapted from TRB (2003).

[a] Excludes costs of downtown bus tunnel built before busway.

costs for bus rapid transit service in Pittsburgh (1989) averaged $0.52 per passenger-trip, and operating costs per vehicle revenue-hour ranged from $50 in Los Angeles to $150 in Pittsburgh (TRB, 2003). A nationwide study by Biehler (1989) showed that bus rapid transit can cost less per passenger trip and per mile than light rail transit, depending on the situation.

Table 4.13 shows the distribution of rail transit operating costs by spending category. Many rail systems involve the use of auxiliary infrastructure such as an automatic train operation (ATO) system, operations control center (OCC), and an automatic fare collection (AFC) system. In 1979, BART let out an ATO contract for $26.2 million (with subsequent change orders, this amount reached $32.7 million). The cost of installing BART's OCC was $2.9 million, while the AFC cost was $4.96 million in 1968 (change orders brought the contract total to $6.6 million) (BART, 2006).

Example 4.9 A light-rail transit system is proposed for the city of Metroville. From the planned schedule it is estimated that 20 rail vehicles will be needed and that

Table 4.12 Average Operating Costs as a Function of Output, by Transit Mode (2005 Dollars)

Performance Measure	Heavy (Rapid) Rail	Light Rail	Bus[a]
Per revenue vehicle-hour	152.29	150.29	76.50
Per revenue vehicle-mile	6.96	11.02	6.42
Per passenger trip	1.61	1.63	1.61
Per passenger mile	0.33	0.44	0.47

Source: Adapted from Black (1995).

[a] Bus operating costs are presented for comparison purposes only.

each vehicle, on its revenue trips, will travel an average distance of 330 miles a day. Assume that the system will operate all year round. What is the expected annual operating cost of the system?

SOLUTION From Table 4.12 average operating cost per revenue vehicle-mile = \$11.02.

Expected travel for all revenue vehicles in one year

$$= (330)(365)(20) = \$2{,}409{,}000 \text{ vehicle-miles}$$

Estimated total operating cost per year

$$= (2{,}409{,}000)(11.02) = \$26{,}547{,}000$$

(*h*) *Bus Transit Capital Costs* Bus transit capital costs involve purchase and preservation of buses, construction and preservation of bus facilities (terminals and stations), and sometimes include construction of a bus-only highway lane. The price per bus depends on the size (length or number of seats), type (transit, suburban, or articulated), number of units purchased, and availability of accessories such as air conditioning, automatic transmission, and wheelchair lifts. For small buses, additional cost factors include the chassis type. Tables 4.14(a) and (b) show the range of unit prices for heavy-duty buses and small buses, respectively. Table 4.15 shows the rehabilitation costs for heavy-duty buses 35 ft in length. The cost of constructing bus facilities ranges from \$120 to \$140 per square foot. The bus transit costs presented in this section are based on historical data, and all costs shown have been adjusted to their 2005 equivalents using FTA cost adjustment factors.

(*i*) *Bus Transit Operating Costs* As Table 4.16 illustrates, some diseconomies of scale are associated with operating bus transit systems, irrespective of the output variable used for the cost function. For example, the cost per vehicle mile, cost per vehicle hour, and cost per peak vehicle are higher for systems of size exceeding 250 buses than they are for systems of size 100 to 250. It should be noted that *vehicle* refers to *revenue vehicle*, which is a vehicle that is in operation over a route and is available to the public for transport at a given time period.

Using data from Cambridge Systematics et al. (1992), the following operating cost functions were developed:

Cost per vehicle-mile

$$= 2.652S^{0.184}\text{PBR}^{0.029} \qquad R^2 = 0.92$$

Cost per vehicle-hour

$$= 41.063S^{0.134}\text{PBR}^{0.247} \qquad R^2 = 0.84$$

Cost per peak vehicle

$$= 11.405S^{0.020}\text{PBR}^{-0.039} \qquad R^2 = 0.83$$

Table 4.13 Distribution of Rail Transit Operating Costs by Spending Category (Percent)[a]

	Heavy (Rapid) Rail (12 systems)	Light Rail (13 systems)	Commuter Rail (10 systems)
Operator salaries and wages	9.30	18.10	11.0
Other salaries and wages	40.7	34.5	29.6
Fringe benefits	29.2	26.2	28.6
Utilities	8.7	9.4	6.1
Other costs	12.1	11.7	24.7
Total	100	100	100

Source: Adapted from Cambridge Systematics et al. (1992).

[a] Percentages are calculated from average costs in each category for all systems reporting.

Table 4.14 Bus Acquisition Costs

(a) Heavy-Duty Buses

Bus Type	Total Number of Buses Purchased	Average Cost per Bus (2005 dollars)	Range of Cost per Bus (2005 dollars)
60-ft articulated	30	472,555	325,842–501,425
40-ft suburban	162	385,608	NA[a]
40-ft transit	686	300,518	270,128–339,348
35-ft transit	45	294,946	290,388–330,907
30-ft transit	43	288,531	253,245–293,764

Source: Adapted from Cambridge Systematics et al. (1992).

(b) Small Buses

Type	Gross Vehicle Weight Rating (lb)	Cost Range[b] (2005 dollars)
Light duty		
Truck cab type of chassis	9,500–12,500	50,649–101,298
Motor home type of chassis	14,500–18,500	7,5974–126,623
Medium duty (rear engine chassis)	16,500–20,500	109,740–185,713
Heavy duty (integrated body)	22,500–26,000	211,038–295,453

Source: Adapted from Johnson (1991).

[a] NA, not available.

[b] Variations in costs are due to size of order, vehicle configuration, and options.

Table 4.15 Rehabilitation Costs for 35-ft Buses

Location	Year	Quantity Rehabilitated (2005 dollars)	Cost per Bus (2005 dollars)	Average Cost per Bus (2005 dollars)
Dubuque	1990	10	136,822	153, 924
Monterey	1990	15	239,438[a]	
Westchester County	1991	20	85,513	

Source: Adapted from Cambridge Systematics et al. (1992).

[a] Includes addition of wheelchair lift, which added about $20,000 per bus to the rehabilitation cost.

where S is the system size (number of buses operated in maximum service), and cost is in 2005 dollars. The *peak-to-base ratio* (*PBR*) is the number of vehicles operated in passenger service during the peak period (morning and afternoon time periods when transit riding is heaviest) divided by the number operated during the off-peak period. These functions can be used to estimate the future operating costs of a proposed bus transit system if the system size and peak-to-base ratio are known. If the latter variable is unknown, the average cost value can be used. More recent average values of operating costs for buses and other public transportation modes are provided in Tables 4.17 to 4.19 but these do not involve the peak-to-base ratio variable.

Table 4.16 Unit Operating Costs of Bus Transit By System Size and Peak-to-Base Ratio

System Size[a]	Peak-to-Base Ratio[b]	Cost per Vehicle-Mile (2005 dollars)	Cost per Vehicle-Hour (2005 dollars)	Cost per Peak Vehicle (thousands of 2005 dollars)
250 or more buses	Ratio 2.00 (16)[c]	7.88	109.87	253,120
	Ratio < 2.00 (18)	8.24	102.22	314,690
100–249 buses	Ratio 2.00 (20)	6.50	98.87	205,230
	Ratio < 2.00 (30)	6.41	81.44	236,020
50–99 buses	Ratio 1.75 (18)	6.48	89.84	176,160
	Ratio < 1. 75 (15)	6.05	94.54	232,600
25–49 buses	Ratio 1.50 (28)	4.87	65.59	164,190
	Ratio < 1.50 (45)	4.93	65.16	198,390
Fewer than 25 buses	Ratio 1.50 (30)	4.43	61.57	141,950
	Ratio < 1.50 (56)	4.38	59.76	172,740
All sizes	All motor buses (363)[d]	5.28	73.03	191,550
	Trolley buses (5)[e]	9.87	104.28	289,040

Source: Adapted from Cambridge Systematics et al. (1992).

[a] Vehicles operated in maximum service.

[b] Vehicles operated in average p.m. peak divided by vehicles operated in average base period.

[c] Numbers in parentheses are the number of bus systems for which data are available.

[d] The complete motor bus database includes several transit systems for which peak–base ratios are not available. Data are missing for a few transit systems for some of the variables above.

[e] Four of the five trolley bus systems are part of systems in the largest size class above.

Table 4.17 Capital and Operating Costs by Travel Mode for Small Cities[a] (2005 Dollars)

Cost Category	Cost Type	Units of Output	Bus	Demand Responsive
Capital costs	Rolling stock	Per passenger trip	0.48	0.74
		Per passenger-mile	0.15	0.21
	Systems and guideways	Per passenger trip	0.05	0.26
		Per passenger-mile	0.02	0.04
	Facilities and stations	Per passenger trip	0.59	0.04
		Per passenger-mile	0.14	0.01
	Total capital costs	Per passenger trip	1.19	1.56
		Per passenger-mile	0.33	0.35
Operating costs	Total operating costs	Per passenger-mile	1.23	3.39
		Per passenger trip	4.02	16.01
		Per vehicle-mile	4.20	3.55
		Per vehicle-hour	59.44	42.77

Source: Adapted from *FTA (2003)*; ECONorthwest et al. (2002).

[a] Data compiled from 20 randomly selected systems with population <200,000.

Example 4.10 The bus transit agency of a certain medium-sized city plans to augment its current fleet by acquiring 45 new 35-ft buses. The brand of buses specified has a service life of 15 years and will need rehabilitation in the sixth and eleventh years of their service life. (a) How much can the agency expect to spend on the capital cost of the new buses over their service life? (b) Assuming a peak-to-base ratio of 1.4 and an average VMT of 36,500 per year, estimate the annual operating cost of the new fleet.

Table 4.18 Capital and Operating Costs by Travel Mode for Medium-sized Cities[a] (2005 Dollars)

Cost Category	Cost Type	Units of Output	Commuter Rail	Heavy Rail	Light Rail	Bus	Vanpool	Demand Responsive
Capital costs	Rolling stock	Per passenger trip	0.02	0.02	0.51	0.60	0.19	3.10
		Per passenger-mile	<0.01	<0.01	0.10	0.08	0.00	0.26
	Systems and guideways	Per passenger trip	0.15	0.15	5.90	0.15	0.44	0.55
		Per passenger-mile	<0.01	<0.01	5.90	0.03	0.02	0.07
	Facilities and stations	Per passenger trip	0.09	<0.01	0.28	0.15	0.14	0.19
		Per passenger-mile	0.01	<0.01	0.11	0.03	0.01	0.02
	Total capital costs	Per passenger trip	0.27	0.16	6.32	0.71	1.29	3.87
		Per passenger-mile	0.04	<0.01	6.11	0.16	0.04	0.35
Operating costs	Total operating costs	Per passenger-mile	0.45	0.30	1.88	0.82	0.89	2.84
		Per passenger trip	21.19	1.97	2.51	3.70	11.60	27.83
		Per vehicle-mile	18.86	6.24	16.12	5.43	1.58	3.55
		Per vehicle-hour	694.52	164.09	185.71	76.33	57.54	53.27

Source: Adapted from FTA (2003); ECONorthwest et al. (2002).

[a] Data compiled from 20 randomly selected system with population >200,000 and <1,000,000.

SOLUTION (a) *Capital cost*: From Table 4.14, the average purchase cost per 35-ft bus = \$294,946. Therefore, the purchase cost of 45 buses = (45)(\$294,946) = \$13,272,570. From Table 4.15, average rehabilitation cost per bus = \$153,924. The total rehabilitation cost of 45 buses = (45)(\$153,924)(2) = \$13,853,160. Therefore, the estimated total capital cost = \$27,125,730.

(b) *Operating cost*: From Table 4.16, average operating cost per vehicle-mile = \$4.93.

The expected travel for all vehicles in one year = (45)(36,500) = 1,642,500 vehicle-miles. The estimated total operating cost per year = (1,642,500)(\$4.93) = \$8,097,525.

4.5.3 Relationships between Transit Operating Costs, System Size, Labor Requirements, and Technology

Tables 4.17 to 4.19 present the capital and operating costs for transit and other public transportation travel modes for small, medium-sized and large cities in the United States (FTA, 2003). These costs are expressed in terms of operational performance measures. Clear differences in cost are seen across mode types and system size (surrogated by city size). An advantage of capital-intensive transit modes, such as rail, is that the smaller share of labor inputs renders the operating costs of such systems less vulnerable to inflation, a particularly important issue given the frequent and sharp increases in transit labor costs relative to the cost of living (Black, 1995). For old transit systems, however, this advantage is outweighed by the fact that such rail systems require a relatively large number of nonoperating workers who maintain the vehicles and right-of-way and carry out management and policing duties. Furthermore, the old rail systems are relatively complicated and require considerable attention to prevent failures. On the basis of 1990 data (Booz Allen Hamilton, 1991), labor expenses (including fringe benefits) comprised the following percentages of total operating costs: old heavy-rail systems, 81.9%; new heavy-rail systems, 70.2%; old light-rail systems, 82.7%; new light-rail systems, 62.3%, and bus transit (20 largest systems), 80.2%.

Clearly, in terms of vulnerability of labor (and thus, operating costs) to inflation, old rail systems seem to have little or no advantage over buses. On the other hand, the lower labor cost fraction (and thus lower inflation risk) of new rail systems is evident and may be attributed to use of state-of-the-art technologies for service and fare collection.

4.5.4 Air Transportation Costs

Denver International Airport (DIA) is the only major airport constructed in the United States in the past 20 years. The cost of DIA, including airport planning, land, and construction was approximately \$60 million

Table 4.19 Capital and Operating Costs by Travel Mode for Large Cities[a] (2005 Dollars)

Cost Category	Cost Type	Units of Output	Commuter Rail	Heavy Rail	Light Rail	Bus	Vanpool	Demand Responsive
Capital costs	Rolling stock	Per passenger trip	2.51	0.28	0.73	0.34	1.42	3.22
		Per passenger-mile	0.20	0.05	0.20	0.08	0.07	0.59
	Systems and guideways	Per passenger trip	1.64	0.78	17.15	0.15	0.14	0.66
		Per passenger-mile	0.12	0.15	4.28	0.03	0.01	0.11
	Facilities and stations	Per passenger trip	1.60	0.61	12.28	0.15	0.03	0.12
		Per passenger-mile	0.07	0.13	1.52	0.03	0.00	0.01
	Total capital costs	Per passenger trip	5.85	1.76	31.08	0.71	1.65	4.60
		Per passenger-mile	0.38	0.36	6.02	0.16	0.09	0.93
Operating costs	Total operating costs	Per passenger-mile	0.53	0.45	4.80	0.83	0.12	3.68
		Per passenger trip	8.95	2.26	6.16	3.84	3.84	30.55
		Per vehicle-mile	14.46	9.16	27.52	8.18	0.63	4.33
		Per vehicle-hour	413.41	199.84	238.44	102.38	24.37	63.68

Source: Adapted from FTA (2003); ECO Northwest et al. (2002).

[a] Data compiled from 20 randomly selected transit systems at cities with population >1,000,000.

per square mile (GAO, 1995). This excludes the cost of capitalized interest, bond discounts, and costs to other users of airport facilities. The annual (1996) cost of operating that airport was $160 million (GAO, 1996) or $9 per domestic "origin-and-destination" passenger. In 2003, a new runway was added at the cost of $52 per square foot.

4.6 ISSUES IN TRANSPORTATION COST ESTIMATION

The cost estimation of transportation projects is a complex undertaking that requires a great deal of engineering judgment. Due consideration should be given to a number of issues that may significantly influence the reliability of cost estimates. Such issues include methods of cost estimation, spatial or temporal adjustments, adjustments for economies (or diseconomies) of scale, sunk-cost considerations, and other factors. These issues are discussed in the following sections.

4.6.1 Aggregated Estimates for Planning vs. Detailed Engineering Estimates for Projects

Most agencies develop unit cost estimates for construction, preservation, maintenance, and operations activities on the basis of market prices of materials, labor, and equipment use. The overall cost of a project is the sum of the product of the unit costs and the quantities of individual pay items. For the final sum of all items, a percentage may be added for contingencies, such as possible cost overruns or unexpected site conditions. Often, for planning purposes, a quick and approximate estimate is needed. As such, instead of obtaining an estimate based on individual pay items, an aggregate value of cost may be derived using historical data from past contracts.

4.6.2 Adjustments for Temporal and Spatial Variations (How to Update Costs)

(*a*) *Temporal Variation (Constant vs. Current Dollars)* From a conceptual and computational standpoint, it is easier to prepare cost estimates in constant (and not nominal) dollar amounts, thus removing the effects of inflation from the analysis. Then if cost streams over time are being compared, the necessary discounting or compounding formula can be used to reflect the opportunity cost. This approach assumes that the interest rate does not include inflation effects. Several cost indices are available to adjust cost information across different years. Examples include the FHWA Federal-Aid Highway Construction Price Index, the Federal Capital Cost Index (Schneck et al., 1995), the FHWA Highway Maintenance and Operating Cost Index, the *Engineering News-Record*'s Construction Cost Index, and the R.S. Means City Construction Index. The Federal

Table 4.20 State Cost Factors, 2004

State	Cost Factor	State	Cost Factor	State	Cost Factor
Alabama	1.21	Louisiana	1.32	Oklahoma	0.95
Alaska	1.30	Maine	1.10	Oregon	1.25
Arizona	0.95	Maryland	0.83	Pennsylvania	0.95
Arkansas	0.95	Massachusetts	0.78	Puerto Rico	1.23
California	1.56	Michigan	1.24	Rhode Island	0.98
Colorado	1.26	Minnesota	1.11	South Carolina	1.32
Connecticut	0.88	Mississippi	1.51	South Dakota	1.19
Delaware	1.51	Missouri	0.81	Tennessee	0.90
District of Columbia	0.56	Montana	1.19	Texas	1.19
Florida	1.19	Nebraska	1.15	Utah	1.33
Georgia	1.15	Nevada	1.49	Vermont	1.27
Hawaii	0.76	New Hampshire	1.30	Virginia	0.80
Idaho	1.12	New Jersey	0.70	Washington	1.39
Illinois	0.90	New Mexico	0.69	West Virginia	0.70
Indiana	1.28	New York	0.90	Wisconsin	1.08
Iowa	0.94	North Carolina	0.97	Wyoming	1.24
Kansas	0.59	North Dakota	1.42	United States	1.00
Kentucky	1.39	Ohio	0.85		

Source: FHWA (2005).

Highway Administration's price trends for federal-aid highway construction are based on information received for the contracts that exceed \$0.5 million. Effective the first quarter of 1990, the FHWA index was converted to a 1987 = 100 base. The *Engineering News-Record*'s Construction Cost Index uses a 1967 = 100 base. Agency costs can be converted to their current or future values using the price indices from the FHWA price trends (see the General Appendix). Price trend prediction using historical data is useful particularly when long-term economic conditions are predictable. A Web address for a price data source is listed in the Additional Resources section of this chapter.

Broad adjustments of cost to reflect the effect of inflation should be done with caution because inflation rates may be different across components of an overall transportation system. For example, general construction costs typically increase at a faster rate than inflation, whereas ITS and other technology-related costs have seen cost reductions.

(*b*) *Spatial Cost Variations* An analyst may wish to estimate the cost of a proposed project on the basis of similar projects implemented at other states. Given the variation of cost of living and costs of production from state to state, it may be necessary to modify costs from other states before they are transferred to others. The FHWA (2005) provides state cost factors for capital improvements (Table 4.20).

4.6.3 Adjustments for Economies of Scale

Although economies of scale have long been recognized in cost analysis of transportation systems, there seems to be an inadequate attempt to develop a formal method to duly adjust cost values to account for this effect in transportation systems evaluation. In most past evaluation studies, cost comparisons have traditionally proceeded on the basis of the cost per unit dimension of each facility. For example, the historical costs of flexible vs. rigid pavements and steel vs. concrete bridges have been compared on the basis of their costs per lane-mile and per square foot, respectively, or on the basis of the sum of costs of their individual constituent pay items per some unit quantity. Such an approach implicitly assumes that a linear relationship exists between the cost of each system or pay item and its size. However, relatively few past studies that analyzed infrastructure cost modeling seem to have explicitly recognized and accounted for the nonlinear relationship that typically exists between project cost and project dimension: The greater the project dimension, the lower the unit cost (cost per lane-mile).

Obviously, cost comparison of any two alternative systems must duly account for economy-of-scale effects, because failing to do so may bias the results against the alterative that typically has smaller project dimensions. For example, comparing the unit costs (cost per lane-mile) of a 20-mile warranty pavement to a 3-mile traditionally constructed pavement (all other characteristics remaining the same) would be inappropriate because compared to the traditional pavement the warranty project (by virtue of its greater length) is likely to yield a smaller unit cost and consequently, a higher effectiveness/cost ratio. It is therefore necessary for the different dimensions of competing systems to be adjusted or "brought" to a common dimension. In this way, any differences in their adjusted costs may reflect the differences in their inherent qualities and not their sizes.

Adjustments for economies of scale may be carried out by establishing a correction factor by which unit costs corresponding to a certain dimension can be translated to yield unit costs corresponding to a certain specified standard project dimension. The only information needed for such adjustment is the unit aggregate cost of the project and the unit aggregate cost function for all projects in the same family. The unit cost function may be developed from historical contract data.

Example 4.11 It is sought to construct a 40-line-mile transit system to link the cities of Cityburg and Townsville. Two types of transit systems have emerged as the popular choices: A and B. Systems A and B have the following cost functions: $C_A = -1.05\ln(X) + 5.2$ and $C_B = 30/X^{0.95}$, respectively, developed on the basis of past projects. C is the cost per line-mile and X is the number of line-miles. The average unit cost of all past projects of types A and B are $207,000 and $285,000 per line-mile, respectively. Would the given unit costs suffice for the evaluation? If not, give reasons and provide the unit costs that should be used for the evaluation.

SOLUTION The solution can best be explained using a sketch in Figure E4.11.

Unless there are data for development of cost function, the use of average unit costs for evaluation should be avoided because they correspond to a certain average system dimension that may not be the same as the dimension of the system being proposed. A significant difference in functional forms of cost functions for alternative designs could lead to very different cost estimates for the system, and this difference is influenced by the planned dimension of the system. In the example above, up to 14.2 line-miles, the unit cost of system A is less than that of system B, but beyond 14.2 line-miles, the unit cost of system A exceeds that of system B. For example, for a system dimension of 40 line-miles, systems A and B are expected to cost $133,000 and $90,000, respectively, per line-mile. These values, not the average costs given, should be used for the agency cost aspects of the evaluation of these systems.

4.6.4 Problem of Cost Overruns

At the feasibility and planning stages of the transportation development process, projected capital and operating costs of public transportation projects have typically been underestimated, as studies have shown that project costs have run over their original bid amounts, often by as much as 5 to 14% (Rowland, 1981; Turcotte, 1996; Wagner, 1998; Bordat et al., 2003). It has been argued that the increasing complexity, increased length of communication channels, and distortion of information feedback associated with larger projects translate to higher cost-overrun rates. Nonquantifiable cost-overrun factors include contract document quality, nature of interpersonal

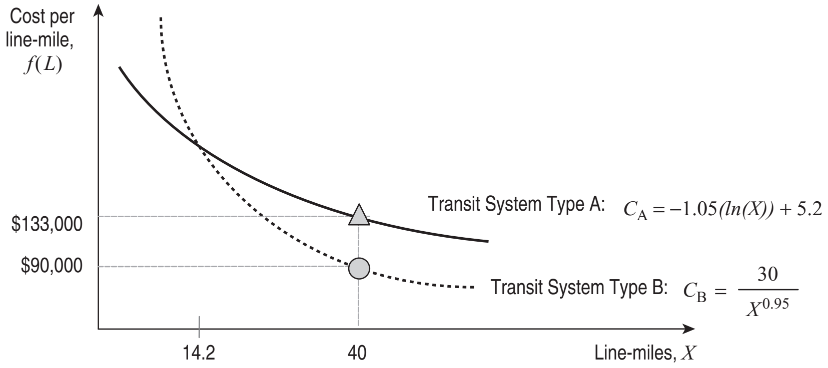

Figure E4.11 Economy-of-scale adjustments.

relations on the project, and contractor policies (Jahren and Ashe, 1990). A FHWA study found that cost overruns were largely attributable to design revisions, difference between the engineer's estimate and the winning bid, and unexpected site conditions, among other reasons (Jacoby, 2001). The causes of overrun costs of transportation projects cited above are attributable to both the contractor and the contracting agency and include inadequate field investigations, unclear specifications, plan errors, design changes, and construction errors (Korman and Daniel, 1998; Wagner, 1998). Also, a FTA study showed that differences between planning and engineering estimates and actual transit construction costs originate from a variety of sources, such as changes in project scope, changes in design standards, unforeseen field conditions, expanded environmental and community requirements, extended implementation periods, underestimation of unit costs, omission of several aspects of project soft costs, and weak estimates of inflation for project capital costs (FTA, 1993). In transportation cost estimation, therefore, sufficient efforts should be made to avoid cost underestimation, such as including a realistic contingency amount or factor to cover possible cost overruns.

4.6.5 Relative Weight of Agency and User Cost Unit Values

An important issue in project economic efficiency analysis or multi-criteria evaluation is the relationship between agency cost and user cost values. Some studies have counted user costs on a dollar-to-dollar basis with agency costs, implying that \$1 of agency cost is equivalent to \$1 of user cost, therefore adding agency costs directly to user costs to obtain an overall project cost. However, there seems to be a trade-off between agency expenses and user cost; alternative designs and preservation strategies that reduce certain user costs often entail higher agency expenses (FHWA, 2002). Second, agency costs appear in agency budgets, whereas user costs do not but rather, reflect the "pain and suffering" of the facility users (Walls and Smith, 1998). Other researchers have therefore cautioned that only a fraction of user costs should be considered and added to agency costs. But what fraction of the total estimated user cost should be used? In other words, what is the ratio of the value of agency cost to user costs? Currently, there seems to be no consensus on the issue, and evaluation has often been carried out using a direct summation of agency and user costs.

The *societal cost* of a transportation project includes all of the money spent on the construction, preservation, and operation over the service life of the facility and its salvage costs. In addition, societal cost includes user costs (vehicle operation, crashes, and travel time) and nonuser costs (noise, air pollution, etc.), and rehabilitation and maintenance. These costs are incurred by producers, consumers, other affected parties, taxpayers, and, ultimately, community residents.

SUMMARY

Transportation cost analysis is a key aspect of transportation systems evaluation. To avoid bias in the evaluation it is essential to consider all cost aspects (agency, user, and community costs). Benefits are often viewed as the reduction in costs (typically, user and community costs) relative to a base alternative, but may also comprise incoming money streams (such as toll revenue) and noncost attributes such as improved aesthetics and community cohesion. Costs may be classified by the source of cost incurrence (agency, user, and community), the nature of variation with the output (fixed and variable), the expression of unit cost (average and marginal), and the time in the facility life cycle at which the cost is incurred (planning/design, construction, operations, and preservation). Agency costs comprise capital costs, operating costs, and maintenance costs. User costs are due largely to vehicle operation, travel time, delay, and safety. Community or nonuser costs are typically adverse impacts (such as noise, air pollution, etc.) suffered not necessarily by facility users but also by persons living or working near the facility.

Typically, the first step in transportation system costing is to describe the physical systems and their operations, followed by costing of the required factors of production. Alternatively, the cost of providing transportation facilities or using transportation services can be expressed as a mathematical function of facility attributes such as physical dimensions, types, constituent material, use, or physical or institutional environment. The costing process may be carried out using cost accounting methods (a process that is laborious, relatively accurate, and used for contract bidding) or statistical modeling that expresses a unit dimension of finished product as a function of treatment or facility characteristics. For user and community costs, preemptive costs differ from after-the-fact costs, as the former involves costs incurred by the agency in ensuring that adverse user costs are minimized, whereas the latter refers to costs incurred by users due to unfavorable conditions associated with that user cost type.

Issues associated with the estimation of costs for transportation projects include aggregated planning estimates vs. detailed engineering estimates, adjustments for temporal variations (how to update costs), adjustments for economies of scale, sunk-cost considerations, uncertainties in transportation systems costing, the problem of cost overruns, the ratio of values of agency and user costs, and realistic estimation of future maintenance and operating costs. Historical cost values and models for transportation systems are available in project reports, at agency Web sites, and from other sources. However, such costs may be used for sketch planning only, as they are either averaged over several projects or specific to a past project with unique conditions. The actual cost of a future transportation alternative may be less or more than that estimated at the planning stage, due to factors such as the presence of extraneous structures, the need for ROW purchase, possible environmental impacts, existing soil and site conditions, project size, project complexity, and method of construction delivery, among others.

EXERCISES

4.1. Compare the life-cycle costs of the following transit alternatives on the basis of their cost per seat: a railcar that costs $1,500,000 has 70 seats and an expected life of 25 years; and a bus that has an initial cost of $200,000, 40 seats, and an expected life of eight years. Assume an interest rate of 6%.

4.2. The annual fixed costs of operating a transit system between cities A and B is $5 million. Also, every passenger-mile costs the transit agency 80.56. Determine **(a)** the annual variable costs; **(b)** the total annual costs; **(c)** the average total costs; **(d)** the average marginal costs. Plot a graph of the total, average and marginal cost functions for the transit operation.

4.3. It is proposed to construct a suitable cost-effective surface transit system to connect an airport and suburb to downtown. The distance is 5 miles, and a station is planned for each 1-mile interval. Two alternatives are being considered: light rail and heavy rail. For each system, determine:

- **(a)** The capital costs for guideways, vehicles, and stations.
- **(b)** The rehabilitation costs of the vehicles (assume rehabilitation intervals of five years). Assume that negligible rehabilitation and maintenance costs of guideway and stations are negligible.
- **(c)** The operating costs per year. Assume that operating costs are uniform for each year.
- **(d)** Draw cash flow diagrams to illustrate the cash outflows for each of 10 years.

4.4. In response to growing passenger and freight demand at Lawrenceville City airport, it is proposed to construct an additional runway. Draw a timetable for release of funds for the various categories of agency costs involved and provide specific examples of costs in each category.

4.5. Discuss the essential differences between the cost accounting and aggregate costing approaches. List the merits and demerits of each approach.

4.6. The fixed operating cost of a transit agency is $50,000 per week. Statistical analyses of historical costs have shown that the variable costs are governed by the following cost function: variable costs $= 0.02V^3 - 4V^2 + 750V$, where V is the weekly ridership. If the average fare is $2.75 per rider, determine the ridership that maximizes revenues of the transit agency. Plot a graph of the total costs, fixed costs, and variable costs. Also, plot a graph of the total cost, average total costs, and marginal total costs.

4.7. The operating costs of a package shipper is governed by the cost function $C = 250V^{3.5}$, where V represents the daily output (number of packages transported in millions). Plot the average and marginal cost functions for $V = 1$ to 5 in unit increments.

4.8. A transportation company has a cost function $C = 10 + 2V + 5V^2$, where C represents the annual total operating costs and V is the number of taxicabs. Provide a plot of the total operating cost function, average operating cost function, and marginal operating cost function. Determine and sketch the elasticity function. Comment on the economy-of-scale implications of the operating costs.

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