Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-97/1356-2		

4. Title and Subtitle	5. Report Date
DEVELOPMENT OF A MULTIMODAL FULL-COST MODEL — MODECOST	March 1996
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Jiefeng Qin, José Weissmann, Michael T. Martello, and Mark A. Euritt	Research Report 1356-2
9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
Center for Transportation Research The University of Texas at Austin 3208 Red River, Suite 200 Austin, Texas 78712-1075	11. Contract or Grant No. Research Project 0-1356
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
Texas Department of Transportation Research and Technology Transfer Office P.O. Box 5080 Austin, TX 78763-5080	Interim
	14. Sponsoring Agency Code

15. Supplementary Notes

Project conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.
Research project title: "Development of an Urban Transportation Investment Model"

16. Abstract

This report summarizes the development of MODECOST, a software program useful in comparing multimodal investment alternatives. First, various cost categories for three modes of a passenger transportation system — auto, bus, and light rail — are identified. This is followed by a discussion of procedures used for annualizing the life-cycle costs of each component of a transportation system. The report also summarizes the unit cost data found in the literature and data received from officials at the Texas Department of Transportation, as well as from staff of other public agencies around the country.

The unit cost data presented include the price of an automobile or transit vehicle, the cost per mile to construct a highway or rail line, and the damage value of air pollutants, among others. In addition, this report describes various algorithms and assumptions utilized to estimate various components of the full cost of transportation systems, including travel time, air emissions, pavement thickness requirements, and the cost of accidents not covered by insurance.

In general, the model allows users to input whatever unit cost values they determine to be appropriate for each mode, while the model's built-in algorithms and assumptions are used to estimate various system parameters. The unit costs are then multiplied by the system parameters in order to obtain an estimate of the full cost of a transportation system alternative.

17. Key Words	18. Distribution Statement
MODECOST, full cost, facility cost, user cost, external cost, agency cost	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	86	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

DEVELOPMENT OF A MULTIMODAL FULL COST MODEL — MODECOST

by

Jiefeng Qin

José Weissmann

Michael T. Martello

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Research Report Number 1356-2

Research Project 0-1356

Development of an Urban Transportation Investment Model

conducted for the

Texas Department of Transportation

in cooperation with the

U.S. Department of Transportation
Federal Highway Administration

by the

CENTER FOR TRANSPORTATION RESEARCH
Bureau of Engineering Research
THE UNIVERSITY OF TEXAS AT AUSTIN

November 1996

IMPLEMENTATION RECOMMENDATION

This report, the second in a series of eight project reports, describes the development of MODECOST, a multimodal full-cost model. This PC-based software model, whose application in specific case studies is described in subsequent project reports, can be implemented as follows:

1. MODECOST can be used by MPOs and other transportation agencies when evaluating a specific corridor's potential transportation alternatives (auto, light rail, and bus) from a full-cost perspective.

Prepared in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

REPORTS FOR THIS PROJECT

1356-1, "Full-Cost Analysis of Urban Passenger Transportation," by Jiefeng Qin, Karen M. Smith, Michael T. Martello, Mark A. Euritt, and José Weissmann. This report examines methods for evaluating and comparing urban passenger transportation projects regardless of mode. After identifying the full-cost approach as an effective tool for undertaking such comparisons, this report describes MODECOST, a full-cost evaluation model developed by the Center for Transportation Research (CTR) of The University of Texas at Austin.

1356-2, "Development of a Multimodal Full-Cost Model — MODECOST," by Jiefeng Qin, José Weissmann, Michael T. Martello, and Mark A. Euritt. This report summarizes the development of MODECOST, a multimodal full-cost model. First, various cost categories for three modes of a passenger transportation system — auto, bus, and light rail — are identified. This is followed by a discussion of procedures used for annualizing the life-cycle costs of each component of a transportation system. The report also summarizes the unit cost data found in the literature and data received from officials at the Texas Department of Transportation as well as from staff of other public agencies around the country.

1356-3, "Full-Cost Analysis of the Katy Freeway Corridor," by Jiefeng Qin, Michael T. Martello, José Weissmann, and Mark A. Euritt. Using a full-cost approach, this report evaluated the different transportation improvement alternatives (developed by Parsons Brinckerhoff Quade & Douglas, Inc.) available for the IH-10 Katy Freeway corridor. Through MODECOST — a computer model based on the full-cost analysis concept — we found that the current facility cannot meet future traffic demands.

1356-4, "The Houston-Harte of San Angelo: A Case Study Application of a Full-Cost Model for Evaluating Urban Passenger Transportation," by Karen M. Smith, Jiefeng Qin, José Weissmann, Mark A. Euritt, and Michael T. Martello. This report evaluates the full costs of transportation alternatives on the Houston-Harte corridor in San Angelo, Texas. The alternatives examined are those considered by the San Angelo District of the Texas Department of Transportation, which include: (1) the continuation of the existing frontage lanes-only configuration and (2) the construction of the mainlanes for completion of the facility. The results of MODECOST — a computer model developed by a Center for Transportation Research (CTR) team — indicate that the addition of mainlanes to the Houston-Harte corridor is both feasible and cost effective.

1356-5, "US 59 Harris County/Fort Bend County: A Case Study Application Of A Full-Cost Model For Evaluating Urban Passenger Transportation," by Michael T. Martello, Jiefeng Qin, José Weissmann, and Mark A. Euritt. This report evaluated transportation improvement alternatives for the US 59 Southwest Freeway corridor from the full-cost, life-cycle approach perspective. The alternatives involve hypothetical facility improvements as well as vehicle occupancy improvements. Our findings suggest that the current facility will not be able to service the projected peak-hour traffic demand; and after running MODECOST — a computer model based on the full-cost analysis concept — we observed that travelers bore a significant amount of external costs, including congestion costs and air pollution costs.

1356-6, "Application of Full Cost of Urban Passenger Transportation Case Study: Northeast (IH-35) Corridor," by Jiefeng Qin, Michael T. Martello, José Weissmann, and Mark A. Euritt. Using a full-cost approach, we evaluated the different transportation improvement alternatives (developed by Rust Lichliter/Jameson) available for the Northeast (IH-35) corridor in San Antonio, Texas. Through MODECOST — a computer model based on the full-cost analysis concept — we found that the current facility cannot meet future traffic demands.

1356-7, "Full-Cost Evaluation of the Northeast Transit Terminal in El Paso, Texas," by Michael T. Martello, Jiefeng Qin, José Weissmann, and Mark A. Euritt. This report presents the results of an evaluation of the cost effectiveness of the Northeast Transit Terminal, an existing Sun Metro bus transit terminal located 23 km north of downtown El Paso, Texas. The evaluation of the transit terminal's cost effectiveness was conducted from a full-cost perspective and consisted of hypothesizing the amount of existing bus ridership that is attributable to the presence of the transit terminal. MODECOST, a computer model developed through this project, was used for the analysis.

1356-8F, "Development of an Urban Transportation Investment Model: Executive Summary," by Michael T. Martello, José Weissmann, Mark A. Euritt, and Jiefeng Qin. This final report summarizes the objectives of the project and provides recommendations for implementation.

DISCLAIMERS

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration or the Texas Department of Transportation. This report does not constitute a standard, specification, or regulation.

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Mark A. Euritt
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Research Supervisors

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SUMMARY

This report summarizes the development of MODECOST, a software program useful in comparing multimodal investment alternatives. First, various cost categories for three modes of a passenger transportation system — auto, bus, and light rail — are identified. This is followed by a discussion of procedures used for annualizing the life-cycle costs of each component of a transportation system. The report also summarizes the unit cost data found in the literature and data received from officials at the Texas Department of Transportation, as well as from staff of other public agencies around the country.

The unit cost data presented include the price of an automobile or transit vehicle, the cost per mile to construct a highway or rail line, and the damage value of air pollutants, among others. In addition, this report describes various algorithms and assumptions utilized to estimate various components of the full cost of transportation systems, including travel time, air emissions, pavement thickness requirements, and the cost of accidents not covered by insurance.

In general, the model allows users to input whatever unit cost values they determine to be appropriate for each mode, while the model's built-in algorithms and assumptions are used to estimate various system parameters. The unit costs are then multiplied by the system parameters in order to obtain an estimate of the full cost of a transportation system alternative.

CHAPTER 1. INTRODUCTION

Without question, the automobile has become the mode of choice among all other forms of urban transportation in the United States. Historically, the automobile has been accepted almost without reservation, inasmuch as it dramatically enhanced an individual's personal mobility. Thus, by 1992, 85.3 percent of all passenger miles of travel made by all modes are related to automobiles. Bus, rail, bicycle, and walking accounted for a total of 2.3 percent, while the remaining relates to air travel.[1] Without a doubt, the prevalence of the auto in our society is vital to economic growth and makes possible the single-family living arrangement that many urban dwellers have preferred.

Yet the extensive use of the private auto has also created new problems for transportation planners, environmentalists, economists, and others, for a variety of reasons. These problems include congestion during peak periods in many major metropolitan areas, air pollution and global weather changing, noise, accidents, high energy usage, land loss, and a decrease of property values. On a more sophisticated level, some economists have argued that "urban auto users do not pay a sufficiently high price for the services that they receive, and as a result the auto is overused from the viewpoint of economic efficiency."[2]

In addressing many of these issues, the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) has emphasized the need for a nationwide multimodal transportation plan. According to the Act, demand management strategies must give equal consideration to highway and transit capacity enhancements. Costs, including indirect social and environmental costs, must also be fully accounted for when comparing modes and management strategies, in order to identify the most cost-effective options.

However, approaches used to measure the effectiveness and costs of private vehicles and other transit modes have not been comprehensive;[3] that is, the costs used in most analyses do not account for differences in benefits among the various transportation modes. The result is that significant cost components have been omitted. For example, highway cost accounting excludes vehicle ownership costs and parking costs, while transit cost accounting omits the cost of the use of the roadway by buses. External social and environmental costs are excluded in all instances. Consequently, this accounting approach compares the different options on different levels. The authors stress the importance of full-cost accounting to avoid favoring certain modes. In order to compare different modes fairly, it is necessary to account for benefits as well as costs. Benefits vary with modes depending upon a number of factors, including travel speed, waiting time, comfort, and the individual preferences of each passenger.

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1 Miller, P., and J. Moffet. *The Price of Mobility — Uncovering the Hidden Costs of Transportation,* Natural Resources Defense Council, 1993.

2 Keeler, T. E., and K. A. Small. *The Full Costs of Urban Transport, Part III: Automobile Costs and Final Intermodal Comparisons*, Institute of Urban & Regional Development, University of California, Berkeley, 1975.

3 Decorla-Souza, P., and Ronald Jensen-Fisher. "Comparing Multimodal Alternatives in Major Travel Corridors," *Transportation Research Record, 1429,* 1994.

In general, private vehicle owners pay high operating and parking fees and generate more tailpipe emissions on a per traveler basis, as compared with high occupancy transit users. The important benefits that accrue to auto users include convenience and low time costs. By including all these costs in the calculations of auto travel expenses, and by comparing them with the similarly estimated full costs of the other two principal modes of urban transport — namely, bus and rail — it is possible to get some idea as to how efficient a transport mode the auto is relative to public transportation. Such an approach will also shed considerable light on the relative full costs of bus and rail transit. In addition, it provides an approach for assessing the transportation investment for different alternatives, which can assist metropolitan transportation planners and decision makers in meeting the new federal and state planning requirements.

This report, the second in a series on the full costs of urban transportation, develops cost estimates to assist urban transportation investment. Multimodal transportation investment can be especially useful for policy purposes, inasmuch as it helps determine under what circumstances an option is more cost effective than another in terms of the resources it uses to provide a given service.

The results of full-cost evaluation include not only infrastructure costs, but also external and user costs. In particular, the inclusion of time value in the calculation of full cost makes the results more meaningful than they otherwise would be. Time value estimates allow us to capture the relative convenience afforded by different modes and to divert resource costs. Thus, while the auto may have higher user-paid costs than bus or rail, it can save a tremendous amount of time and create convenience for its users, which cannot be matched by bus and rail. Similarly, if external costs are not included, some important drawbacks of auto travel would not be accounted for.

The primary objective of this research project (and of the reports) is to provide metropolitan planning organizations (MPOs), the Texas Department of Transportation (TxDOT), and other policy makers with a method for investing public transportation dollars most efficiently. Specifically, the project has the following three objectives:

1. Perform an in-depth literature review and identify the full system costs of urban transportation.
2. Develop a working model for analyzing transportation investment from a system cost perspective to justify resource allocation in the face of increased competition for limited funds.
3. Support the development of an ISTEA-mandated public transit management system.

In the previous report, we explored the environment that has created the need for a more coordinated multimodal urban transportation system. At the same time we reviewed the literature on full-cost approaches to transportation system planning (thus fulfilling the first objective).

This report serves as the basis for formulating our working model for analyzing transportation investment from a system perspective, and promoting more effective multimodal transportation planning and development in Texas. It also provides a technical description of MODECOST,[4] the computer software program that can be used for calculating urban transportation costs.

In terms of report organization, this first chapter has outlined the report and has provided background. Chapter 2 identifies the key components that affect the cost of driving, including infrastructure costs, external costs, and user costs. A total system cost analysis of transportation modes relies on the determination of the collective effect of the cost components. A total system cost strategy is recommended as an analysis framework.

Chapter 3 introduces a set of engineering economic theories that will be used throughout the report. Chapter 4 builds on the findings of the previous chapter (Chapter 2) to present an analysis model of the full cost of multimodal urban passenger transportation. The model determines the annualized costs of urban passenger transportation under a given circumstance. The last chapter, Chapter 5, summarizes and discusses the findings of this research and, finally, provides recommendations for future research.

4 MODECOST is the software developed and registered by J. Qin, M. Martello, M. A. Euritt, and J. Weissmann at the Center for Transportation Research, The University of Texas at Austin.

CHAPTER 2. ANALYTIC FRAMEWORK AND COST COMPONENTS

Both the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) and the Clean Air Act Amendments of 1990 (CAAA) have prompted the need for a more comprehensive approach to evaluating transportation options. Policy makers must examine various transportation modes and compare alternatives that increase capacity with those that limit or shift demand.

In order to compare various multimodal transportation alternatives (which are dependent on time and locations), it is necessary to assess such alternatives on a comparable basis. Knowledge of the costs of different kinds of travel is critical in choosing the potential policy that may affect the distribution of transportation.

The quantitative costs are divided into three general categories: infrastructure costs, external costs, and user costs for all modes — car, bus, and rail users. Infrastructure costs include direct construction, maintenance, rehabilitation, and other government expenses directly associated with providing transportation services. External costs include congestion, pollution, and energy use, which are indirect costs. User costs represent those expenses that come directly from user pockets, including the costs to purchase, register, maintain, and operate a vehicle.

This project provides cost estimates for passenger travel in an urban transportation system. As such, the main focus is the auto, insofar as more than 85 percent of all passenger miles traveled in the U.S. are made by auto. The full costs of private vehicle transportation are shown in Figure 2.1. The total costs consist of three categories, namely, facility cost, external cost, and user cost. The costs associated with facilities include all the material and labor used to provide a transportation system (e.g., right-of-way, construction, rehabilitation, and maintenance costs). The payment for these costs mainly comes from user fees and property taxes.

External costs, or externalities, include travel time cost, accident cost not covered by insurance, pollution cost, incident delay cost, and other costs. Most external costs, such as air pollution, influence both highway-users and non-highway-users, while travel time cost is primarily imposed on highway users. A significant issue concerns the reckoning of travel time as a social cost. Many researchers omit all non-congestion travel time costs, arguing that "when deciding to make a trip, a driver implicitly considers his or her own time costs of the travel."[1] Congestion costs involving both delays and inefficiencies in transportation are certainly a cost to society. Non-congestion costs are also borne by consumers. The last part of the total cost is that dealing mainly with those costs coming out of the users' pockets.

As a part of highway users, the costs of truck freight movements are included in the private vehicle transportation. As trucks share the same highway facilities with passenger cars and buses and produce the same kinds of external costs, they directly influence the results of passenger cars and buses. In addition, some of them are even for personal travel purpose, like pickups, vans, and utility vehicles. As the purpose of this study is to identify the full costs of

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[1] Miller, P., and J. Moffet (1993).

urban passenger transportation, the vehicle costs and operating costs of those trucks with commercial purposes are not included in the personal vehicle cost part.

The bus data are presented in Figure 2.2. The transit buses share the same roadway facility as personal vehicles. As indicated earlier, the travel time cost rather than the congestion cost of bus travelers is included in our study. Indeed, congestion cost is an important constituent of total social cost. The public often perceives the level of congestion as a principal index of how a regional transportation system functions. But if non-delay-related travel time, such as that associated with access time, waiting time, and transfer time for transit trips, is not included in the analysis, the total transportation-related social cost is not accounted for, the result being that the social cost is likely to be underestimated. Unlike private vehicle users, bus travelers pay fares that partly cover the expenses by transit agencies to purchase buses, construct stations, etc. In order to avoid double counting, the user costs (fares) are eliminated from the framework and are replaced by the actual transit agency cost used to operate and maintain the transit system.

Figure 2.3 presents the rail cost components. Rail facility costs include the cost of rail vehicles, guideways, stations, right-of-way, yards, and shops. The external costs of rail users consist of travel time (both in-vehicle and out-of-vehicle time), air pollution costs, and other costs. Like bus travelers, rail users pay a certain amount for fares each year (which go to rail transit agencies for constructing and maintaining the rail facilities). The money is omitted from the framework so as to avoid double counting.

Chapter 4 will assess each cost component for each mode. It starts with privately operated vehicles (autos and trucks), then goes on to describe the cost components for bus and rail.

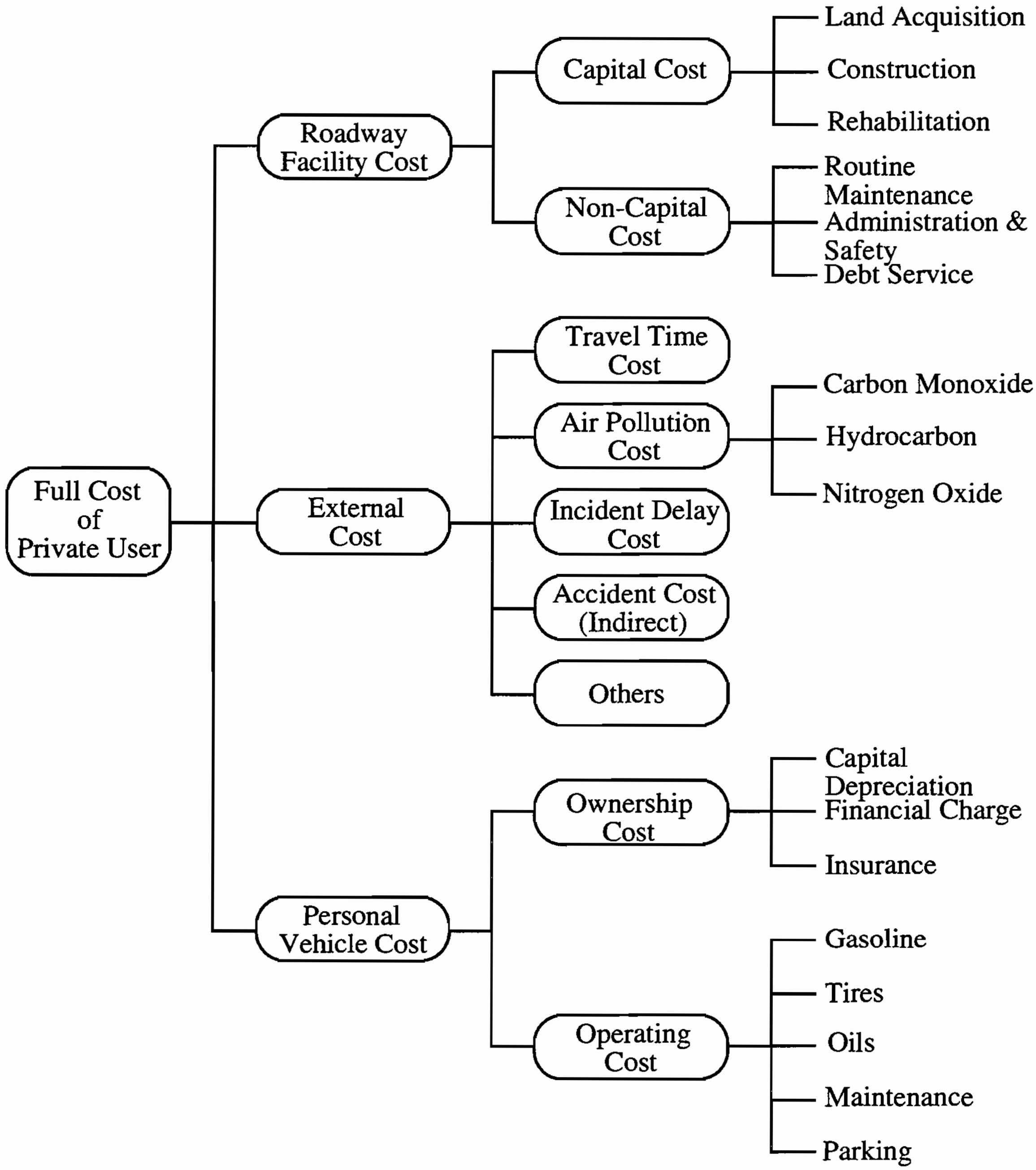


Figure 2.1 Elements of full costs for private auto users

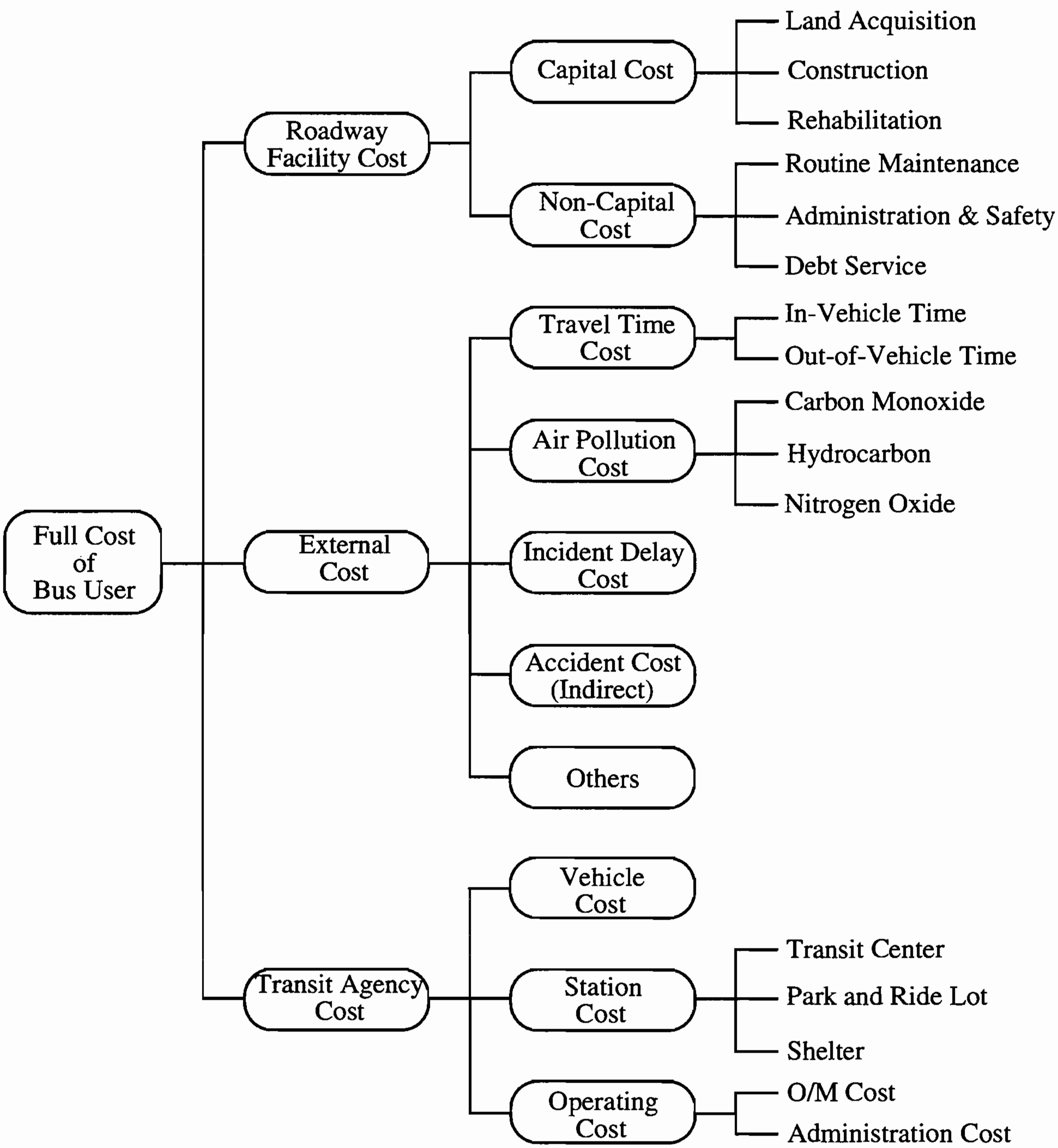


Figure 2.2 Elements of full cost for bus users

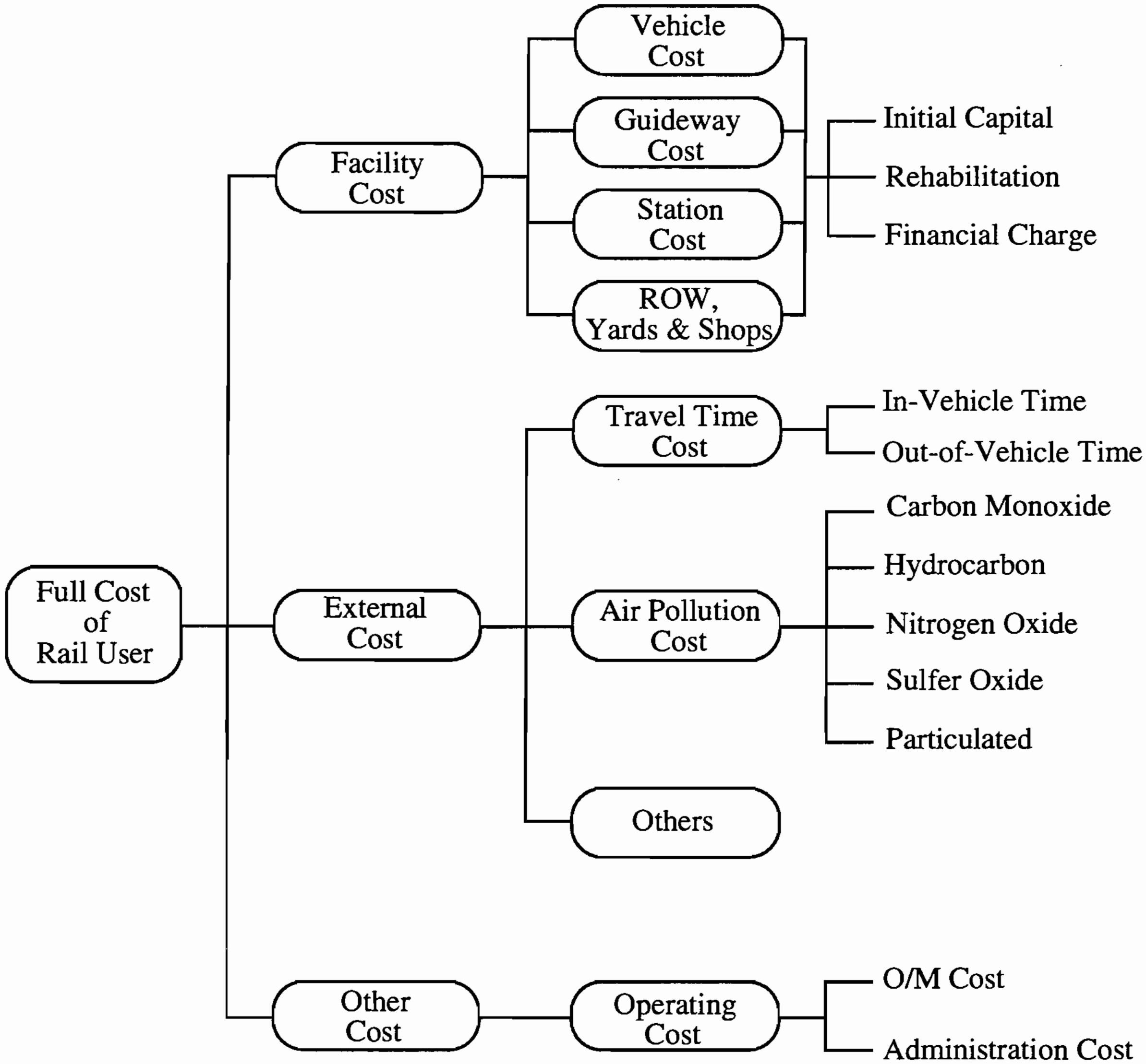


Figure 2.3 Elements of full cost for rail users

CHAPTER 3. REVIEW OF ENGINEERING ECONOMICS AND LIFE-CYCLE COST

Before discussing the engineering models, it is necessary for us to first present some background on the subject of engineering economics. Engineering economics is "decision making based on comparisons of the worth of alternative courses of action with respect to their costs."[1] Such decision making also makes use of discounted cash-flow evaluations, as well as techniques adapted from financial accounting, decision theory, operations research, and other disciplines. The purpose of this section is to introduce the basic terminology of engineering economy and to outline the fundamental concepts that form the basis for economic analysis.

3.1. ENGINEERING ECONOMICS

Most structures and systems, including roadway infrastructures, are brought into being and operated over a life cycle that begins with the initial identification of a need and ends with disposal action. In general, the life cycle involves two major phases: acquisition and operation.

Life-cycle cost embraces all costs, both non-recurring and recurring, that occur over the life cycle. During the acquisition phase, non-recurring costs are incurred, and these constitute the first cost of the structure or system. During operation, the structure or system also imposes recurring costs. Life-cycle cost analysis considers all costs over the life cycle and seeks an economic balance between the cost of acquisition and the cost of operation.

Since most components in a system may have different life cycles, annualized life-cycle cost is used throughout this study. Before explaining annualized life-cycle cost, we define the following symbols, which are shown in Figure 3.1.

P = value or sum of money at a time denoted as the present,

F = value or sum of money at some future time,

A = a series of periodic, equal amounts of money, and

n = number of years in a life cycle.

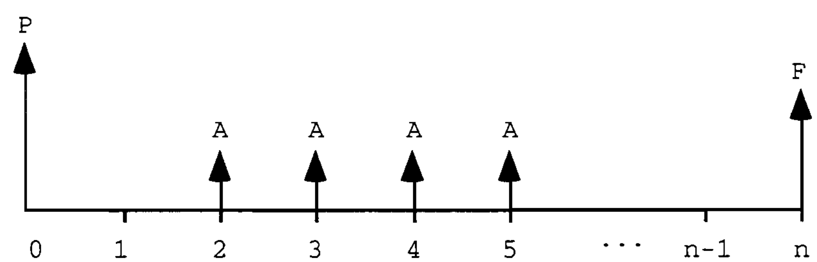


Figure 3.1 Cash-flow diagram

[1] Riggs, J. L. *Engineering Economics*, McGraw-Hill, 1977.

The symbol P and F represent single-time occurrence values; A occurs each interest period for a specified number of periods with the same dollar value. P, F, and A can be converted from one to another by given n and i. The following four conversion processes are achieved through the interest formulas.

3.1.1. Present-Worth Factor (P/F, i, n)

The effect of this factor is to convert the future value F to the current worth P. The formula is:

$$P = F \cdot (P / F, i, n) = F \cdot \frac{1}{(1+i)^n} \qquad \text{(Eq 3.1)}$$

where (F/P, i, n) is the compound-amount factor.

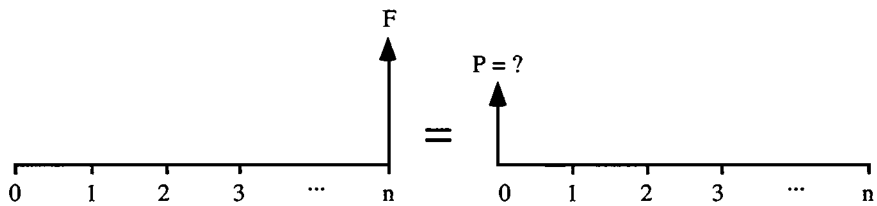


Figure 3.2 Cash-flow diagram of present-worth factor

3.1.2. Capital-Recovery Factor (A/P, i, n)

The capital-recovery factor is used to determine the amount of each future annuity payment required to accumulate a given present value when the interest rate and number of payments are known. The formula is:

$$A = P \cdot (A/P, i, n) = P \cdot \frac{i \cdot (1+i)^n}{(1+i)^n - 1} \qquad \text{(Eq 3.2)}$$

where (A/P, i, n) is the capital-recovery factor.

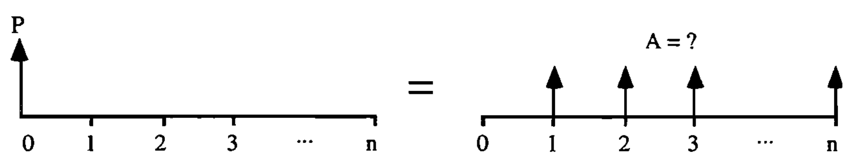


Figure 3.3 Cash-flow diagram of capital-recovery factor

3.1.3. Series-Present-Worth Factor (P/A, i, n)

The present value of a series of uniform end-of-period payments can be calculated as:

$$P = A \cdot (P/A, i, n) = A \cdot \frac{(1+i)^n - 1}{i \cdot (1+i)^n} \qquad \text{(Eq 3.3)}$$

where (P/A, i, n) is the series-present-worth factor.

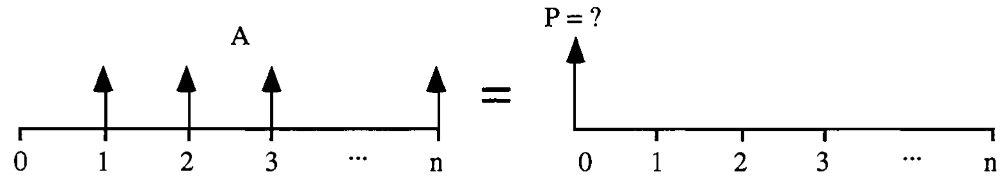


Figure 3.4 Cash-flow diagram of series-present-worth factor

3.1.4. Sink-Fund Factor (A/F, i, n)

A fund established to accumulate a given future amount through the collection of a uniform series of payments is termed a sinking fund. The formula for A is:

$$A = F \cdot (A/F, i, n) = F \cdot \frac{i}{(1+i)^n - 1} \qquad \text{(Eq 3.4)}$$

where (A/F, i, n) is the sink-fund factor.

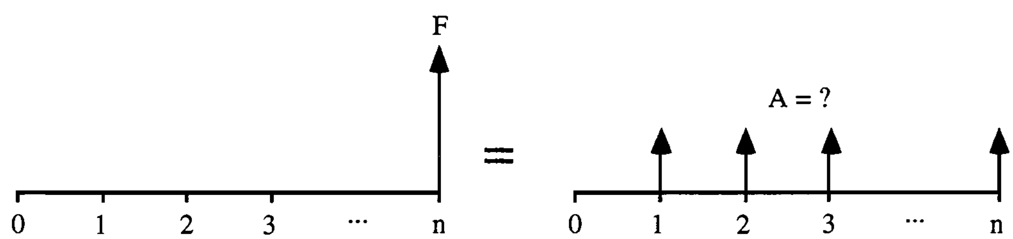


Figure 3.5 Cash-flow diagram of sink-fund factor

3.2. ANNUALIZED LIFE-CYCLE COST

The annualized life-cycle cost is defined as one of an equivalent uniform series values, A, beginning with the first year and lasting throughout the life-cycle, as shown in Figure 3.6. The equivalence means that sums of money on both sides in the figure can be equal in economic value.

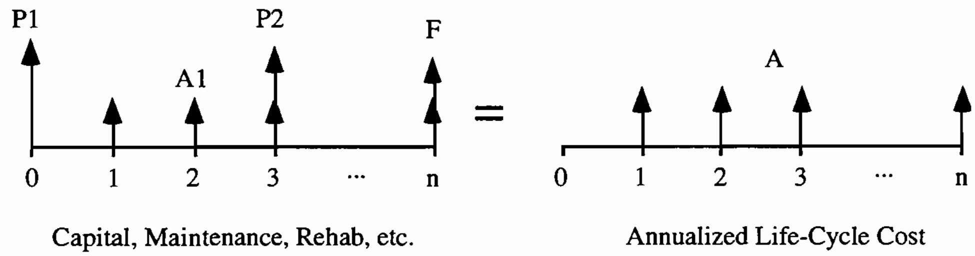


Figure 3.6 Cash-flow diagram of annualized life-cycle cost

The above gives the general concepts of annualized life-cycle cost. In many cases, the initial capital cost is borrowed money, which has a loan rate and loan period different from the discount rate and lifetime. In such cases, the interest charged must be included in the calculation of annualized life-cycle cost. Figure 3.7 illustrates the cash-flow diagram of such a process.

The initial principal, P, is annualized by using loan rate and loan period. The recalculated present worth P_1 includes the possible interest charged by the lender. Finally, the annualized life-cycle cost is calculated from P_1. This is represented mathematically as

$$A = P \cdot (A / P, r, m) \cdot (P / A, i, m) \cdot (A / P, i, n) \qquad \text{(Eq 3.5)}$$

This technique or concept will be used throughout the report to identify the life-cycle cost.

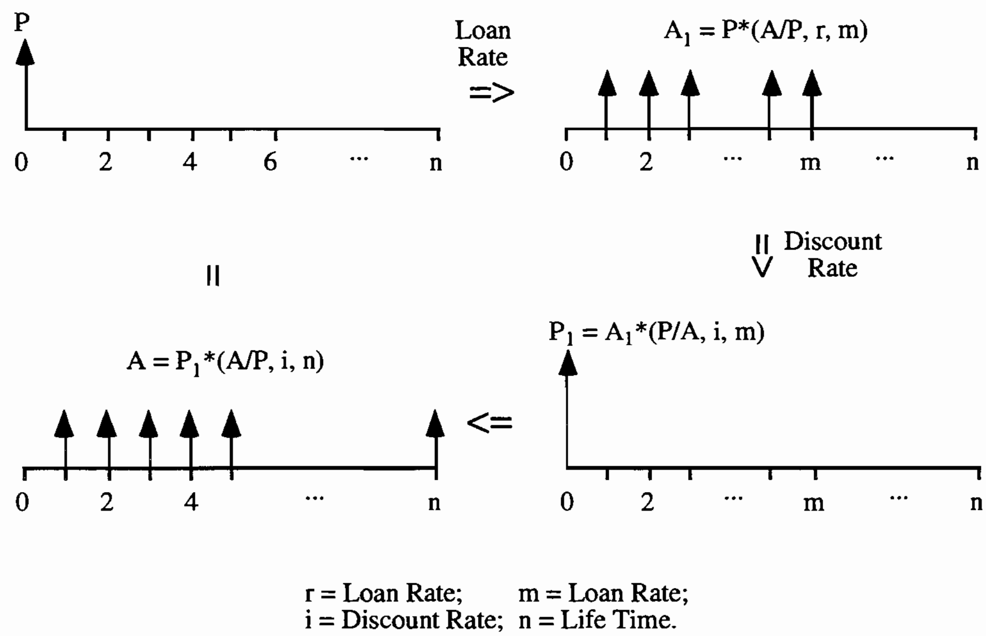


Figure 3.7 Cash-flow diagram of life-cycle cost with interest charge

CHAPTER 4. MODELING THE COST COMPONENTS

The analytic framework for full-cost components described in Chapter 2 set out a general methodology for the determination of urban passenger transportation costs. This chapter describes possible approaches to model and quantify the cost component, as well as the data requirements and the possible data sources. The approaches are intended to be broadly applicable to diverse settings and types of transport. The chapter starts with private vehicle transportation cost, then goes on to discuss bus- and rail-user cost.

4.1. PRIVATE-USER COST

Private users are defined as all passenger cars and all trucks having both commercial and personal travel purposes. Although the objective of this study was to identify the full costs of urban passenger transportation, trucks are included in our study not simply because some of them are used for personal travel purposes, but because they also directly influence the travel behavior of passenger car and bus users. As shown in the following sections, trucks are the major contributors to road damage; consequently, they increase the facility cost of the system. As mentioned in the earlier chapter, the personal vehicle cost part includes only the personal transportation vehicles, namely, all passenger cars and some light trucks. (In 1992, about 75 percent of all light trucks, including pick-up trucks, vans, utility vehicles, and station wagons, were used for personal travel purposes.[1]) These passenger cars and light trucks represent the major source of personal vehicle cost.

4.1.1. Facility Cost Estimation

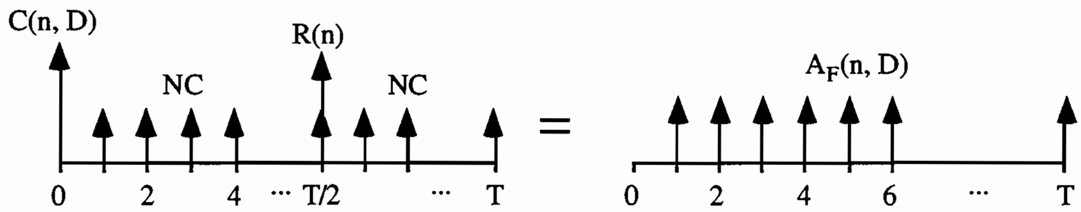
Before describing the facility cost estimation model, we should identify the different roadway functional classes. The three types of roadways under consideration in our study include urban expressways, arterials, and local streets. Urban expressways include those streets having complete access control (i.e., no access from commercial or residential property) and which carry a relatively large number of through trips daily. Arterials carry a moderate number of through trips daily — usually with no direct residential access. Local streets carry local traffic and serve adjacent land use; they also provide access to adjacent residential land.

Road facility costs have two dimensions: capacity and durability. Capacity is needed to accommodate vehicle flow without excessive congestion and is typically increased by adding lanes. Durability — or long-term pavement serviceability — is needed to accommodate a cumulative flow of heavy vehicles without their imposing excessive pavement damage and the concomitant costs to both public agencies and highway users. Durability is typically enhanced by increasing pavement thickness. The highway system in the U.S. is a multi-user system, serving all kinds of passenger cars, trucks, and buses. For any given highway system, highway planners and engineers must

1 From *Truck Inventory and Use Survey, 1992*, among 4,051,500 pickups, panels, vans, utilities, and station wagons in Texas, 3,036,500 light trucks are for personal transportation.

provide an appropriate number of lanes of sufficient pavement thickness to accommodate both congestion and pavement damage.

The facility cost of roadways includes both capital cost and non-capital cost. The capital cost is a periodic cost and includes land acquisition costs, construction costs, and rehabilitation costs. The non-capital cost is an annual cost. The annualized facility cost in the accounting process can be expressed as:



$C(n, D)$ = Construction. and L.A. Cost
NC = Non-Capital Cost
$R(n)$ = Rehabilitation Cost
T = Life Time

$A_F(n, D)$ = Annualized Facility Cost
T = Life Time

Figure 4.1 Cash-flow diagram of annualized facility cost

The following sections present the equations used for determining all cost components. Since highways are not isolated systems, we must consider passenger cars, trucks, and buses simultaneously in calculating facility costs.

4.1.1.1. Capital Cost: The capital cost of a roadway facility includes the cost of land acquisition, construction, and periodic rehabilitation. The construction and real estate costs are directly related to the thickness of the pavement and the width of the pavement, or number of lanes. A feasible expression of construction and real estate cost is

$$C(n, D) = k_0 + k_1.n + k_2.n.D \qquad \text{(Eq 4.1)}$$

where

$C(n, D)$ = the construction and land acquisition cost, in dollars per mile,

n = the number of lanes in one direction, and

D = durability or road thickness — for rigid pavements, it is the pavement thickness in inches; for flexible pavements, it is known as the structure number, a linear combination of surface course, base, and subbase thickness.

The first term following the equal sign in Eq 4.1 is a fixed capital cost, which is affected by real estate value (excluding traffic lanes). The cross section of an expressway includes a 12.2-m frontage road plus border, an 18.29-m outer separation, a 4.5-m median, and 3.66-m traffic lanes. The right-of-way excluding traffic lanes is assumed to be 65.6 m. The arterial is assumed to have

2.44-m shoulders and 6.1-m borders. A 6.1-m median is also provided. Right-of-way width without traffic lanes is 23.16 m. The proposed cross-section for these roadways is shown in Figure 4.2. It is assumed that the right-of-way is extended 12.8 m beyond the local street, which will accommodate sidewalks at the margin.[2] Using a real estate value of σ dollars per square foot, which depends on the analysis area, Table 4.1 lists the values of k_0 for expressways, arterials, and local streets.

The second term in the above equation represents the non-pavement capital cost. This term specifies the cost of excavation, drainage and landscaping, and the real estate value of traffic lanes themselves (a value that does not rely on pavement thickness). The values for k_1 of different roadways are chosen to render capital cost as a linear approximation of the estimated equation. The result is that, for urban expressways, the construction cost (excluding right-of-way) per lane-mile is equal to a value of \$433,870.[3] And k_1 is then determined by subtracting a pavement cost of \$142,208 per lane-mile, assuming a standard freeway pavement thickness of 25.4 cm and a pavement unit cost of \$2.02 per square yard per inch. For urban arterials, the corresponding values are \$285,000 per lane-mile and a standard pavement thickness of 12.7 cm. The value of k_1 for local streets is then derived in proportion to its right-of-way dimension.

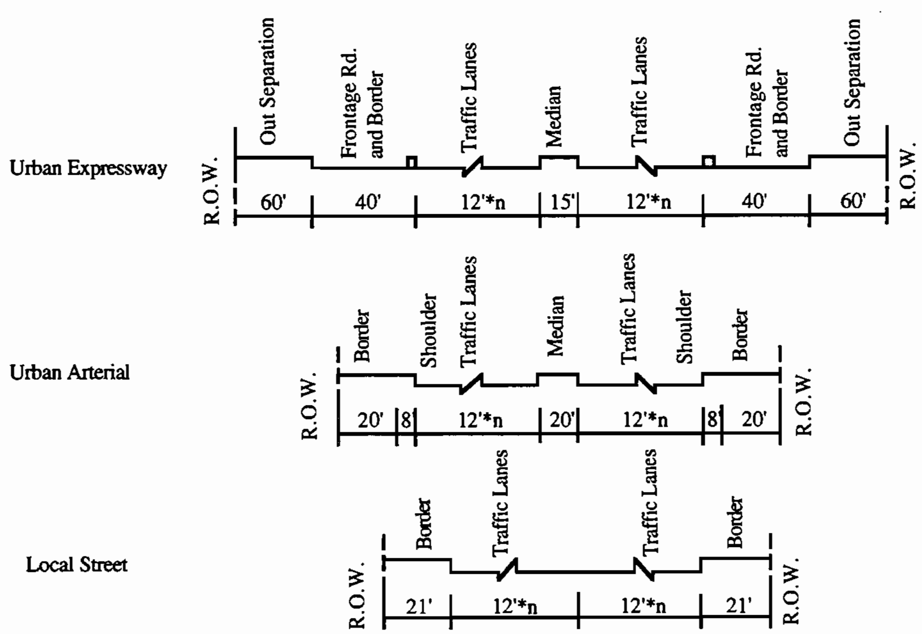


Figure 4.2 Cross-sections of roadways (not to scale)

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2 The dimension of right-of-way, shoulders, borders, etc., are derived from *A Policy on Geometric Design of Highways and Streets*, American Association of State Highway and Transportation Officials, Washington, D.C., 1990.

3 Reported by TxDOT in *User Manual for Software Developed to Quantify the Emissions Reductions and Cost-Effectiveness of Selected Transportation Control Measures.* Prepared for Houston-Galveston Area Council by Sierra Research, Inc., 1994.

Table 4.1 The coefficients in 1992 dollars

Coefficient/Road Category		Value
k_0 ($/mile)	Urban Expressway Urban Arterial Local Street	1,135,200σ 401,280σ 221,760σ
k_1 ($/lane-mile)	Urban Expressway Urban Arterial Local Street	291,662+63,360σ 213,896+63,360σ 118,206+63,360σ

It is worth noting that the above data represent general information, and as such may not be appropriate for some facilities owing to variations among regions. Accordingly, users of MODECOST may change any of these values.

The last term on the right-hand side of Eq 4.1 is the cost of the pavement itself, which is proportional to the volume of the pavement. In order to calculate this portion of the cost of a pavement, it is necessary to know its physical characteristics (type of pavement, materials, number of layers, layer thickness, etc.), which essentially depend on the number and magnitude of load applications the pavement is expected to sustain and the traffic the pavement is expected to serve. In this study, pavement design parameters are obtained by the AASHTO method. For flexible pavement, layer thicknesses are further calculated using a linear programming optimization procedure.

The procedure for estimating the pavement initial construction cost is illustrated in the following figure. Traffic volume and distribution, coupled with the axle weight distributions by vehicle class, constitute the required input for the design part of the cost estimation procedure. In the AASHTO method, mixed traffic composed of various axle loads and types is converted to a design traffic value expressed as the number of equivalent 18,000 lb single-axle load applications (18-kip ESALs) through the use of a load equivalence factor.

The number of 18-kip equivalent single axle loads (ESALs), W, representative of a given mixed traffic composition throughout a specified analysis period, is given by

$$W = \sum_{k}\sum_{j}\sum_{i}\left(e_{ijk} \cdot p_{jk} \cdot N_k\right) \qquad \text{(Eq 4.2)}$$

where

W = total ESALs generated by vehicles during analysis period,

e_{ijk} = load equivalence factor (ESAL) for axle i in weight category j of vehicle class k,

p_{jk} = percentage of class k vehicles in weight category j, and

N_i = total number of class k vehicles during analysis period.

There are eleven vehicle groups included in the above ESAL calculation. They are:

- passenger cars
- 2-axle single unit trucks
- 3-axle single unit trucks
- 3-axle semi-trailers
- 4-axle semi-trailers
- 5-axle semi-trailers
- 6-axle semi-trailers
- 5-axle full-trailers
- 6-axle full-trailers
- 2-axle bus
- 3-axle bus

We determined that the division of the above vehicle classes is not sufficient for ESAL calculation. As the weights carried by the vehicles within the same group may be substantially different, we divided each vehicle class into eleven weight categories. These are:

- 8,000 lb - 10,000 lb*
- 10,001 lb - 17,000 lb
- 17,001 lb - 24,000 lb
- 24,001 lb - 31,000 lb
- 31,001 lb - 36,000 lb
- 36,001 lb - 42,000 lb
- 42,000 lb - 62,000 lb
- 62,001 lb - 80,000 lb
- 80,001 lb - 98,000 lb
- 98,001 lb - 116,000 lb
- 116,001 lb - 160,000 lb

The historical data show that the ESALs of passenger cars are so small that they can be ignored in the calculation. The ESALs of other vehicle classes depend on the load of the vehicle, pavement thickness, weight distribution, etc. The following ESAL calculations are based on the early AASHO (currently AASHTO) test. The basic equations for rigid pavements developed from the AASHTO road test are:

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* 1 lb = 0.45 kg

$$e_{ijk} = \left[\frac{\left(L_{ijk} + L_2\right)^{4.62}}{(18+1)^{4.62}} \right] \left[\frac{10^{G_t/\beta_{18}}}{\left(10^{G_t/\beta_{18}}\right)\left(L_2^{3.28}\right)} \right] \qquad \text{(Eq 4.3)}$$

where

L_{ijk} = load of axle i in weight category j of vehicle class k, in kip,

L_2 = axle code (1 for single axle, 2 for tandem axles, and 3 for tridem axles),

$G_t = \log \dfrac{4.2 - P_t}{4.2 - 1.5}$,

P_t = serviceability at the end of time t, 2.5 in this study,

$\beta_t = 1.0 + \dfrac{3.63\left(L_i + L_2\right)^{5.20}}{\left(D_r + 1\right)^{8.46} L_2^{3.52}}$,

$\beta_{18} = 1.0 + \dfrac{3.63(18+1)^{5.20}}{\left(D_r + 1\right)^{8.46}}$, and

D_r = rigid pavement durability, or thickness, of a rigid pavement slab.

For flexible pavement, load equivalence factors for axle weight category i are given by

$$e_{ijk} = \left[\frac{\left(L_{ijk} + L_2\right)^{4.79}}{(18+1)^{4.79}} \right] \left[\frac{10^{G_t/\beta_{18}}}{\left(10^{G_t/\beta_{18}}\right)\left(L_2^{4.331}\right)} \right] \qquad \text{(Eq 4.4)}$$

where

L_{ijk} = load of axle i in weight category j of vehicle class k, in kip,

L_2 = axle code (1 for single axle, 2 for tandem axles, and 3 for tridem axles),

$G_t = \log \dfrac{4.2 - P_t}{4.2 - 1.5}$,

P_t = serviceability at the end of time t, 2.5 in this study,

$\beta_t = 0.4 + \dfrac{0.081\left(L_i + L_2\right)^{3.23}}{\left(D_f + 1\right)^{5.19} L_2^{3.23}}$,

$\beta_{18} = 0.4 + \dfrac{0.081(18+1)^{3.23}}{\left(D_f + 1\right)^{5.19}}$, and

D_f = flexible pavement durability, or the structure number of the pavement.

The structure number for flexible pavement is the strength indicator; it is defined as a linear combination of the layer thicknesses, where the coefficients represent the relative strengths of the respective layer materials.

In the above total ESALs calculation, structure number or slab thickness is one of the inputs. However, this structure number or slab thickness may not be sufficient to withstand the total number of ESALs. The structure number or slab thickness necessary to sustain the total ESAL, W, for rigid pavement is (from AASHTO)

$$\log W = -0.47701 + 7.35\log(D_r + 1) - 0.06 - \frac{0.19837}{1 + \frac{16240000}{(D_r + 1)^{8.46}}}$$

$$+3.42\log\frac{650\left(D_r^{0.75} - 1.132\right)}{690.016\left(D_r^{0.75} - 1.1347\right)} \qquad \text{(Eq 4.5)}$$

And for flexible pavement, the equation becomes

$$\log W = -0.5757 + 9.36\log(D_f + 1) - 0.2 - \frac{0.15261}{0.4 + \frac{1094}{(D_f + 1)^{5.19}}} + 0.51161 \qquad \text{(Eq 4.6)}$$

Pavement construction costs were obtained by producing hypothetical designs of typical pavements for all combinations of vehicle classes. Flexible pavements were designed to have a service life of 30 years, while rigid pavements were designed to have a service life of 40 years.

Equations 4.5 and 4.6 might be different than originally assumed in Equations 4.3 and 4.4. Therefore, a number of iterations, as shown in Figure 4.3, are required to converge the structure number or slab thickness input into the previous step with that output from the latter one.

Rigid pavements were assumed to be made of portland cement, the cost of which was estimated at \$2.02 per square yard per inch, or \$14,220 per lane-mile per inch. The AASHTO method was employed in calculating slab thicknesses for rigid pavements.

The AASHTO design procedure directly yields the thickness of rigid, single-layered pavements. Since flexible pavements usually consist of a surface course, a base course, and a subbase course, there is an infinite number of thickness combinations among these three layers that can yield the appropriate structural number.

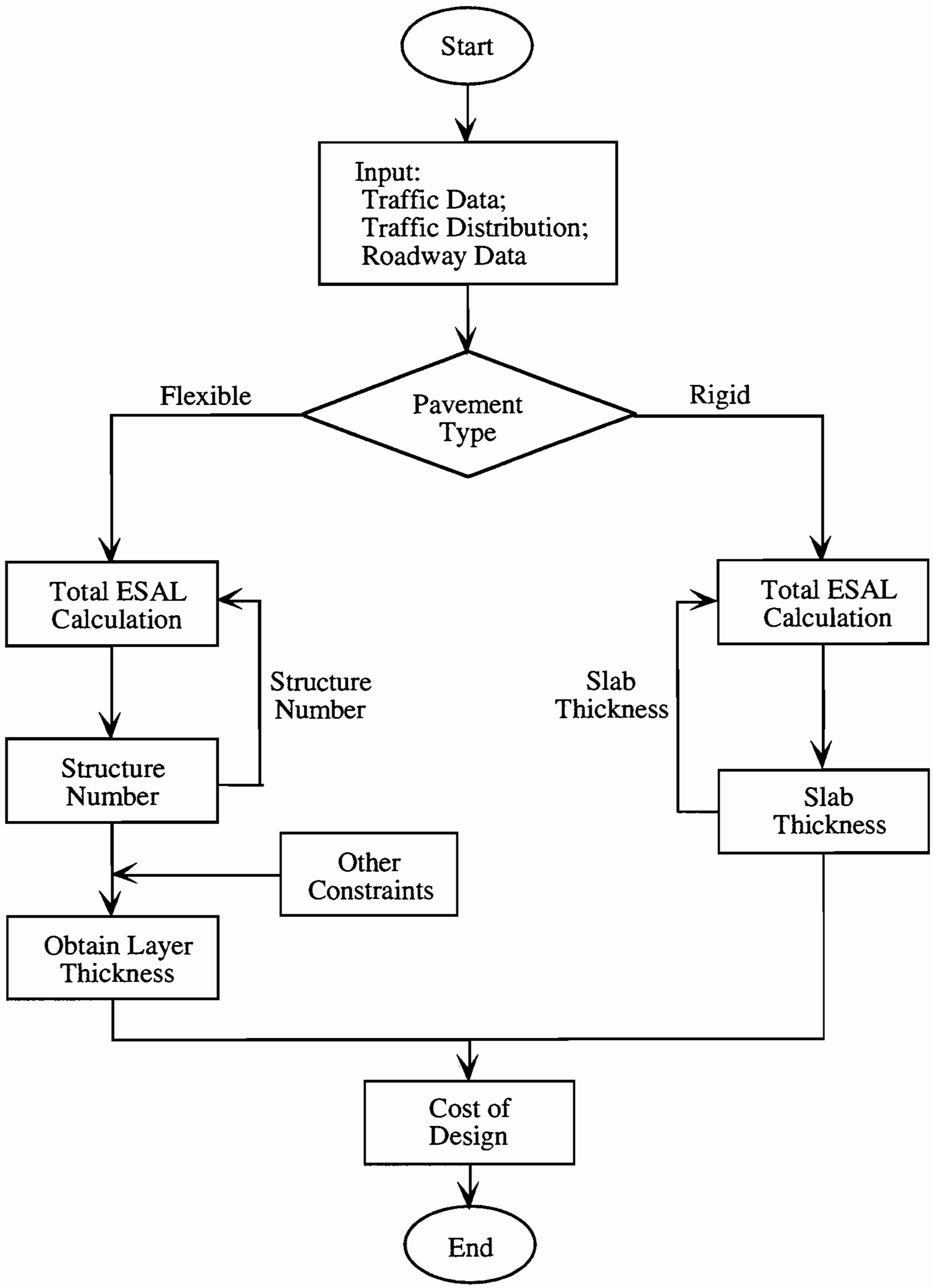

Figure 4.2. Pavement cost estimation approach

In this study, the best pavement design is considered to be the least expensive one among those which meet the basic requirements of (1) structural strength, (2) overall pavement thickness, and (3) individual layer thickness. The thickness selection problem may be formulated as a linear programming problem as follows:

$$\text{Minimize} \quad 1.724X_1 + 1.713X_2 + 0.292X_3 \qquad \text{(Eq 4.7)}$$

subject to constraints:

$$0.44X_1 + 0.34X_2 + 0.11X_3 \geq D_f \qquad \text{(Eq 4.8)}$$
$$X_1 \geq 1.5 \qquad \text{(Eq 4.9)}$$
$$X_2 \geq 8 \qquad \text{(Eq 4.10)}$$
$$X_3 \geq 6 \qquad \text{(Eq 4.11)}$$
$$X_1 + X_2 + X_3 \geq 20 \qquad \text{(Eq 4.12)}$$
$$X_1 \geq 0, \quad X_2 \geq 0, \quad X_3 \geq 0 \qquad \text{(Eq 4.13)}$$

where X_1, X_2, and X_3 are the thicknesses of the surface course, base course, and subbase course, respectively.

The objective function (Eq 4.7) minimizes the pavement cost per square yard, using \$1.724 per square yard per inch material cost for the surface course, \$1.713 per square yard per inch for the base course, and \$0.292 per square yard per inch for the subbase. Constraint 1 (Eq 4.8) establishes the minimum structural strength required by assuming strength coefficients of 0.44, 0.34, and 0.11 for the surface, base, and subbase courses, respectively. Constraints 2, 3, and 4 (Eq 4.9 through Eq 4.11) define minimum thickness required for each layer. Constraint 5 (Eq 4.12) specifies the minimum overall thickness. And the last constraint (Eq 4.13) represents the non-negativity condition of linear programming.

The rehabilitation cost, on a per mile basis, is directly related to the width of the pavement. The function of the overlay cost is assumed to be a linear function of number of lanes, or mathematically

$$R(n) = k_3 n \qquad \text{(Eq 4.14)}$$

where $R(n)$ represents rehabilitation cost, in dollars per mile.

The value of k_3 is derived from the average contract price for an overlay in Texas. More than 50 sections of overlay were analyzed. Among these, the lowest price was \$50,000 per lane per mile, while the highest was \$300,000 per lane per mile. The cost of most sections was about \$20 – \$30 per square yard, corresponding to \$141,000 – \$211,000 per lane per mile. In our study, k_3 is suggested to be equal to \$175,000 per lane per mile for rigid pavement and \$225,000 for flexible pavement. The rehabilitation of a section of pavement occurs at the mid-point of its service life, namely, at 15 years for flexible pavement and at 20 years for rigid pavement.

4.1.1.2. Non-Capital Costs: Non-capital roadway expenditures include routine maintenance, administration, safety, and debt service, among other costs. The most expensive category among non-capital expenditures is routine maintenance and operations. It includes regular expenditures required to keep a roadway in usable condition (e.g., patching repairs, pavement marking, snow and ice removing, signals, etc.). We estimate an annual routine maintenance cost for rigid pavements to be \$6,000 and \$10,000 for flexible pavements.[4] These estimates are used as defaults in the "Default Values" window under the heading of "Maintenance."

Both administration and highway safety expenditures have grown substantially over the past few years.[5, 6] Spending for administration, including research and planning, represents 7 percent of the total expenditure, while safety now represents 9 percent of all spending. These costs can be accounted for in the "Default Values" window under the heading of "Other Cost," by inputting the value either as an annual cost or as a percentage of the total capital costs. Our estimate of a default value for these costs is 16 percent of the total capital cost.

On the basis of the work done so far, the annualized total facility cost equation in a life cycle for roadways may be characterized as follows (in dollars per year)

$$A_F(n, D) = \eta \cdot \left[C(n, D) + R(n) \cdot (P/F, i, T/2)\right] \cdot (A/P, i, T) \cdot L \qquad \text{(Eq 4.15)}$$

where

$A_F(n, D)$ = facility cost, which is a function of n and D, and in dollars per year,

i = the discount rate,

T = the life time of the pavement.

$C(n, D), R(n)$ = described in Eq 4.1 and Eq 4.14, respectively,

L = the length of corridor(s), in miles, and

η = coefficient used to capture the non-capital costs, which is a user input in MODECOST.

The cash-flow diagram in the above equation refers to Figure 4.1.

4.1.2. External Cost

In order to ensure that motor vehicle users bear their fair share of the total costs of driving, it is necessary to determine the external costs (or "externalities") of motor vehicles. External costs

4 Estimates provided by Dr. José Weissmann, P.E., The University of Texas at San Antonio.

5 Lockwood, S. C., H. B. Caldwell, and G. G. Williams. "Highway Finance: Revenues and Expenditures," *Transportation Research Record, 1359*, 1992.

6 *Highway Statistics* (1992).

are the external effects of transportation modal use that have some influence on society or the environment, and which are not reflected directly in market transactions. The hidden costs include travel time cost, air pollution cost, accident cost, and incident delay cost, among other costs. These costs are the result of transportation development and use.

The following sections describe the monetary values of the external costs. Since the external costs are produced through transportation use, the costs presented in this report are based on a per-mile-per-vehicle basis. The annual costs are simply the product of the annual vehicle miles of travel (VMT) and the unit costs. In addition, owing to the variation in VMT during the life-span of the facility, the annual total external costs in different years are annualized by using the life-cycle cost concept detailed in section 4.1.2.6.

4.1.2.1. Travel Time Cost: This section deals with the user cost resulting from travel time. Faster travel confers benefits mainly because it saves time, which is a value. Travel time, or travel speed, is a function of many things, including the maximum design speed of the road and vehicle density. In this study, a two-regime traffic-flow model is used. The congested-flow regime and the non-congested-flow regime capture the different travel time by travelers at different times of the day.

i) Equivalent Passenger Car Factor

The usual traffic stream is composed of a mixture of vehicles: passenger cars, trucks, buses, and occasionally recreational vehicles. Consideration must be given to the composition of traffic in deciding on the volumes of traffic that will be used in determining vehicle travel time.

The effect that trucks and buses have in contributing to congestion on highways is discussed in the *Highway Capacity Manual* (HCM).[7] Detailed procedures are outlined for converting volumes of mixed traffic to equivalent volumes of passenger cars. Factors for converting trucks, buses, and recreational vehicles to equivalent passenger car traffic on roadways are given in Table 4.2. In MODECOST, the equivalent values of terrain input by users are used to convert the number of trucks and buses to an equivalent number of passenger cars.

Table 4.2 Equivalency factor

Vehicle Type	Terrain		
	Level	Rolling	Mountainous
Truck	1.7	4	8
Bus	1.5	3	5
Recreational Vehicle	1.6	3	4

Source: *Highway Capacity Manual.* Transportation Research Board, Special Report 209, Washington, D.C., 1985.

7 *Highway Capacity Manual.* Transportation Research Board, Special Report 209, Washington, D.C., 1985.

ii) Travel Time on Expressway

a) Congested Period

A congested period is defined as the period during which the demand exceeds capacity. In this study, the point bottleneck model[8] is applied. In our approach, we ignored the upper part of the speed-volume curve and considered only the queuing delay that occurs when capacity is exceeded. This type of model can be characterized as a deterministic queuing behind a bottleneck. It is assumed in this study that the traffic demand pattern will take the form of the rectangular shape shown in Figure 4.4.

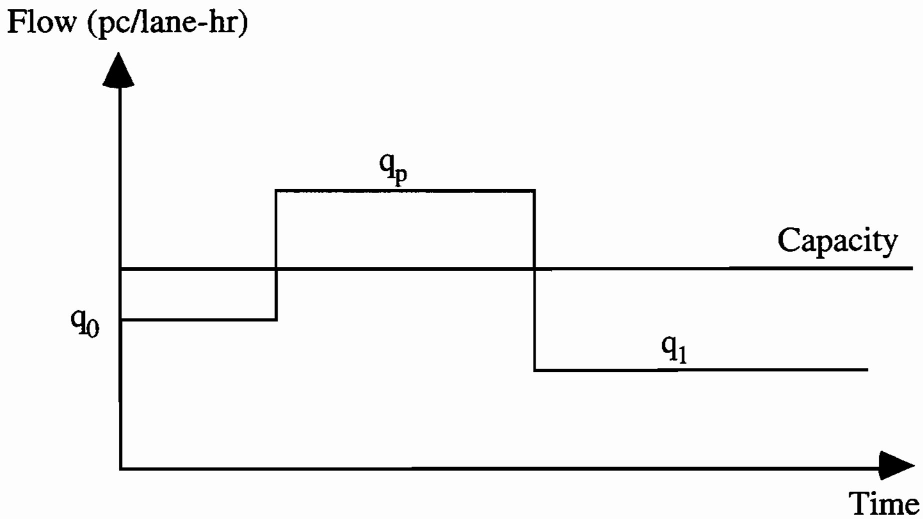

Figure 4.4 Peak-hour demand pattern

Prior to the period when demand exceeds capacity, the average demand rate is assumed to be a constant q_0, and less than capacity C. At time t_1 the demand jumps to q_p which is greater than capacity. It maintains this for (t_2-t_1) time before reaching the post-peak demand q_1, e.g.

$$q(t) = \begin{cases} q_0 & t \le t_1 \\ q_P & t_1 < t \le t_2 \\ q_1 & t_2 < t \end{cases} \qquad \text{(Eq 4.16)}$$

where q(t) is in passenger cars per lane per hour.

For any arrival at time t, the queuing delay d(t) in this case is shown to be

8 May, A. D., and H. E. M. Keller. "A Deterministic Queuing Model," *Transportation Research, Vol. 1*, 1967.

$$d(t) = \begin{cases} 0 & t \le t_1 \\ \left(\frac{q_p}{C} - 1\right)(t_2 - t_1) & t_1 < t \le t_2 \\ \left(\frac{q_p}{C} - 1\right)(t_2 - t_1) - \frac{q_1}{C}(t_2 - t_1) & t_2 < t \le t_3 \\ 0 & t_3 < t \end{cases} \quad \text{(Eq 4.17)}$$

where

t_1 = the time at the beginning of the period when demand exceeds capacity,

t_2 = the time at the end of the period when demand exceeds capacity, and

t_3 = the time at which the queue is dissipated.

The average travel time by a passenger car or truck during the period when demand exceeds capacity, over a 1.6-km (1-mile) segment is then

$$\begin{aligned} T &= \frac{1}{v_c} + \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} d(t)dt \\ &= \frac{1}{v_c} + \left(\frac{q_p}{C} - 1\right)\frac{t_2 - t_1}{2} \\ &= \frac{1}{v_c} + \left(\frac{Q_p}{nC} - 1\right)\frac{H}{2} \end{aligned} \quad \text{(Eq 4.18)}$$

where

T = travel time by an auto or truck, in hours per mile,

v_c = the speed at capacity, in mph,

Q_p = one-directional hourly equivalent demand, in passenger cars per hour,

C = one-lane capacity of expressway, or 2,000 passenger cars per hour per lane (pcphpl),

H = duration of period when demand exceeds capacity, in hours, and

n = the number of lanes in one direction.

b) Uncongested Period

During the uncongested period, the demand is less than capacity. A modified Greenshields formula[9] is used to calculate the travel time:

$$v = (v_f - v_{min})\left(1 - \frac{k}{k_j}\right)^a + v_{min} \qquad \text{(Eq 4.19)}$$

where

v_f = free-flow speed, or 65 mph for an urban expressway,

v_{min} = minimum speed, equal to 5 mph,

k_j = jam density, about 150 cars/mile,[10] and

a = a parameter, in the range of 0.85 to 1.1. It is set to 1 in this study.

By applying flow (q), density (k), and the speed (v) relationship, the auto or truck travel time over a 1.6-km (1-mile) segment is then

$$\begin{aligned} T &= \frac{2}{v_f + \sqrt{v_f^2 - \frac{4q_{np}}{k_j}(v_f - v_{min})}} \\ &= \frac{2}{v_f + \sqrt{v_f^2 - \frac{4Q_{np}}{nk_j}(v_f - v_{min})}} \end{aligned} \qquad \text{(Eq 4.20)}$$

where

T = travel time, in hours per mile,

Q_{np} = the uncongested period equivalent demand in one direction, in pcphpl, and

n = the one-directional number of lanes as described before.

9 Hu, T., R. Rothery and H. S. Mahmassani. *DYNASMART: DYnamic Network Assignment-Simulation Model for Advanced Road Telematic*, Technical Working Paper DTFH61-90-C-0074-TWP1, Center for Transportation Research, The University of Texas at Austin, 1992.

10 Drake, J., J. Schofer, and A. May. "A Statistical Analysis of Speed Density Hypotheses," *Highway Research Record, 154*, 1967.

Therefore, the travel time with or without congestion on an hours-per-vehicle-per-mile basis can be expressed as

$$T(Q, n) = \frac{1}{v_c} + \left(\frac{Q_p}{nC} - 1\right)\frac{H}{2} \qquad \text{(Eq 4.21)}$$

and

$$T(Q, n) = \frac{2}{v_f + \sqrt{v_f^2 - \frac{4Q_{np}}{nk_j}(v_f - v_{min})}} \qquad \text{(Eq 4.22)}$$

respectively,

where

T(Q, n) = unit travel time which is a function of Q and n, in hours per mile, and

C, Q_p, Q_{np}, H, v_f, v_{min}, and k_j are as described earlier.

iii) Travel Time on Arterials and Local Streets

a) Intersection Delay

The travel time on arterials or local streets includes intersection delay and running time. The formulas from the HCM[11] are used in our study to calculate the average speed of the vehicles. The intersection delay[12] is formulated as

$$D = 26.6 \cdot \frac{(1-G)^2}{\left(1 - G \cdot \frac{Q}{nC}\right)} + 173 \cdot \left(\frac{Q}{nC}\right)^2 \left(\frac{Q}{nC} - 1 + \sqrt{\left(\frac{Q}{nC} - 1\right)^2 + 16 \cdot \frac{Q}{nC^2}}\right) \qquad \text{(Eq 4.23)}$$

where

D = the delay at the intersection, in seconds per intersection,

G = green time ratio, which is assumed to be 0.6 for arterials and 0.45 for local streets,

Q = one-directional equivalent demand, in passenger cars per hour,

n = the number of lanes in one direction,

11 *Highway Capacity Manual* (1985).

12 The following formula is derived from the *Highway Capacity Manual* (1985), using a 70-second cycle length.

C = the capacity of the arterial or local street, which equals 1,080 pcphpl for arterial and 810 pcphpl for local street.[13]

b) Running Time

The running time on arterials or local streets is directed to the length of the block. The following data obtained from HCM Table 11.4 arterial I and HCM Table 11.4 arterial III, as shown in Table 4.3, are used in this project.

c) Travel Time on Arterials or Local Streets

The unit travel time cost (per vehicle per mile) on arterials or local streets in dollars per vehicle per mile can be written as

$$T(Q, n) = \frac{D \cdot N_I + T_R}{3600} \qquad \text{(Eq 4.24)}$$

where

$T(Q, n)$ = unit travel time and is a function of Q and n, in hours per mile,

D = one-vehicle delay at an intersection formulated in Eq 4.23,

N_I = the average number of intersections in 1-mile lengths, in intersections per mile, and

T_R = the running time by a vehicle defined in Table 4.3, in seconds per mile.

Table 4.3. Vehicle running time

Segment Length (mi)	Arterial (sec/mi)	Local Street (sec/mi)
< 0.05	136	227
0.05 - 0.10	131	180
0.10 - 0.15	125	150
0.15 - 0.20	120	140
0.20 - 0.25	115	132
0.25 - 0.30	110	125
0.30 - 0.40	102	120
0.40 - 0.50	96	115
0.50 - 1.00	93	110
> 1.00	90	105

Source: The data in the table were obtained from the *Highway Capacity Manual* (1985). Interpolation and extrapolation are used for some values.

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[13] Following the *Highway Capacity Manual* (1985), the capacity of an intersection on an arterial or local street is 1,800 passenger cars per hour green per lane, which transfers to 1,800 * 0.6 = 1,080 pcphpl for arterial, and to 1,800 * 0.45 = 810 pcphpl for a local street.

iv) Total Travel Time Cost

The traffic volume in an average day varies. The traffic during the peak period is certainly more congested than that during an off-peak period. Thus, the speed during a peak period may be lower and, consequently, the time cost may be higher. In order to capture the variation in the traffic occurring during the various hours of the day, we divided a normal working day or a typical weekend into four periods — morning peak period, afternoon peak period, day, and night. The traffic demand and mix during each period, as well as the duration of the period, are the inputs to Eq 4.21, Eq 4.22, and Eq 4.24; these are used to calculate the unit travel time cost on a per-vehicle-per-mile basis for each period. The annual total travel time costs are the product of VMT and unit travel time cost,[14] or mathematically

$$A_{time} = \alpha \cdot \beta \cdot \sum_{i=1}^{8} \left(T(Q, n)_i \cdot VMT_i \right) \qquad \text{(Eq 4.25)}$$

where

A_{time} = annual total travel time cost by auto users, in dollars per year,

α = the average vehicle occupancy, in passengers per vehicle,

β = the travelers' value of in-vehicle auto travel time, in dollars per passenger per hour,

$T(Q, n)_i$ = the unit travel time in each period, defined in the above equations,

VMT_i = the annual auto or truck VMT on the corridor during the ith period, and

i = the ith period, namely, morning peak, afternoon peak, day, and night.

The way to relate travel cost and travel time is through the value of travel time, β. But while there is a vast literature on the theory and estimation of the value of travel time, it is extremely difficult to arrive at a single number for use in a given study. The value of travel time is most likely related to the wage rate, the income level, the extent to which the traveler enjoys traveling relative to working, the ability of the traveler to adjust his/her hours devoted to various alternative activities to traveling, the location of the study area, and a number of other factors. In any event, an assessment of the value of travel time is beyond the scope of this study. Thus, we leave the value of travel time, β, open as a user input in MODECOST. Instead of using a single value for travel time, users can run a set of alternative scenarios with different values, and determine how sensitive the results are to the values assumed.

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14 In the MODECOST software we developed for this project, the user inputted total VMT is divided in proportion to the shares in different periods.

In addition to the value of travel time, average vehicle occupancy, α, is another sensitive input to the model. The Nationwide Personal Transportation Survey in 1990[15] showed that the average auto occupancy was 1.161 for working trips, 1.869 for other-purpose intracity trips, and 1.61 for all trips.

4.1.2.2. Pollution Cost: Air pollution from tailpipe emissions can impair the health of humans and other animals, can damage agricultural crops, and can limit visibility. It is a typical example of an externality. Those who generate air pollution usually do not bear the full cost of the problem. On the other hand, those who reduce air pollution do not receive the full benefit of the air pollution reduction.

There are two ways to estimate the damage caused by air pollution. One way establishes air pollution standards at an optimal level and requires the polluters to meet those standards. The other way charges the polluters a pollution fee at the level of the difference between the social marginal damage and the private marginal damage of air pollution. The former refers to the control cost method, while the latter refers to the damage cost method.

The main advantage to the use of control costs is that they are easier to determine than damage costs, because data on the costs of control are more readily available. The major disadvantage is that control costs may bear little or even no relationship to the damages imposed on society by the relevant pollutants.

We used the damage cost method to estimate the dollar value of damages caused by air pollution. The method involves three steps: (1) identification of emission sources; (2) estimation of emissions; and (3) calculation of monetary values of each pollutant. These three steps are discussed below.

i) Identification of Emission Sources

Air pollution, commonly referred to as "smog," is the contamination of the ambient air by chemical compounds or particulated solids in a concentration that adversely affects living organisms. The main air pollutants include carbon monoxides (CO), hydrocarbons (HC), nitrogen oxides (NO_x), sulfur oxides (SO_x), soot-like particulates (PM), and carbon dioxides (CO_2). Vehicles generate a significant portion of the emissions in urban areas. These emissions can vary according to the type of engine, the mode of operation, the fuel composition, etc. SO_x and PM emissions are mainly generated by stationary sources, and are excluded in our study. CO_2, which is the primary cause of global warming, will be considered in another section.

Carbon monoxide (CO) is formed in the combustion process as a result of the incomplete burning of fuel; it is always present in small quantities in the exhaust regardless of the air/fuel ratio. The greater proportion of fuel there is in the air/fuel mixture, the more CO is produced. This implies that during idling and decelerating, the CO concentration is very high. It decreases during acceleration and high-speed cruising.

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15 Hu, P. S. "Changes in Americans' Journeys-to-Work," presented at the 1993 Annual Meeting of the AAG, Atlanta, GA.

Hydrocarbon is incompletely burned or evaporated gasoline or solvents. Its concentration is high during idling and deceleration, as opposed to concentrations associated with cruising and acceleration.

Nitrogen oxide is a product of the burning of surfer-rich fossil fuel, which is formed during the combustion process. It increases with peak combustion temperature. In other words, a higher level of NO_X is produced during acceleration and high-speed cruising; lower concentrations exist during deceleration and idling.

ii) Estimation of Emissions

The power generated by the engine is a function of engine speed and throttle opening. In most cases, however, variables such as engine speed and throttle opening are not readily available. Therefore, air pollution is generally estimated by using vehicle speed and acceleration. On the basis of this finding, the following model is proposed:

$$m_p = \frac{\beta_1}{v} + \beta_2 \cdot v^2 + \beta_3 \cdot a \cdot v \qquad \text{(Eq 4.26)}$$

where

m_p = emission rate of pollutant p (CO, HC, or NO_X),

v = vehicle speed,

a = vehicle acceleration rate, and

β_i = coefficients.

The first term on the right side of the equation captures the emission rate during the idle and deceleration period. The second term deals with the emission rate during the vehicle cruising period, which is consistent with the fact that the drag force on the vehicle cruising at a speed v is proportional to the square of the speed, v^2, because of the aerodynamic force. The last term is the emission rate during the acceleration period. There is a strong correlation between the product of acceleration and speed and the vehicle's accelerating emissions. The product of acceleration and speed is equivalent to power per unit mass. Therefore, the power expended by a vehicle during acceleration is proportional to the product of acceleration rate and speed. As power demand approaches engine capacity, vehicles tend to burn fuel less efficiently, resulting in high emission rates. Acceleration rates drop slowly when vehicle speed is low. However, they drop sharply after the speed exceeds 40 mph. Based on this observation, it is reasonable assume that vehicle accelerating rates are a function of speed in the form of

$$a = \beta_4 + \beta_5 \cdot v^{1/2} \qquad \text{(Eq 4.27)}$$

Hence, Eq 4.26 can be rewritten as

$$m_p = \frac{\alpha_1}{v} + \alpha_2 \cdot v + \alpha_3 \cdot v^{1.5} + \alpha_4 \cdot v^2 \qquad \text{(Eq 4.28)}$$

where

m_p = emission rate of pollutant p (CO, HC, or NO_x), in gram per mile,

v = vehicle speed, in mph, and

α_i = coefficients.

By using the data from MOBILE4.0, we found the following relations between vehicle speeds and emission rates. The relations are grouped according to four vehicle classes, namely, light-duty gasoline vehicles (LDGV), representing all passenger automobiles; light-duty gasoline-trucks (LDGT), which represent pick-ups and minivans; heavy-duty gasoline vehicles (HDGV), which represent most 2-axle single-unit trucks; and heavy-duty diesel trucks (HDDV), which represent the remaining trucks and buses. The formulas are listed in Equations 4.29 through 4.40.

LDGV:

$$m_{HC} = \frac{26.29463}{v} - 0.866522 + 0.280275 \cdot v - 0.067588 \cdot v^{1.5} + 0.004486 \cdot v^2 \qquad \text{(Eq 4.29)}$$

$$m_{CO} = \frac{237.07805}{v} - 7.450332 + 3.093110 \cdot v - 0.886121 \cdot v^{1.5} + 0.067083 \cdot v^2 \qquad \text{(Eq 4.30)}$$

$$m_{NOx} = \frac{2.176306}{v} + 0.453768 + 0.162195 \cdot v - 0.045865 \cdot v^{1.5} + 0.003436 \cdot v^2 \qquad \text{(Eq 4.31)}$$

LDGT:

$$m_{HC} = \frac{35.00395}{v} - 0.326018 + 0.296447 \cdot v - 0.078155 \cdot v^{1.5} + 0.005484 \cdot v^2 \qquad \text{(Eq 4.32)}$$

$$m_{CO} = \frac{322.46469}{v} - 9.405258 + 3.799829 \cdot v - 1.100497 \cdot v^{1.5} + 0.084199 \cdot v^2 \qquad \text{(Eq 4.33)}$$

$$m_{NOx} = \frac{3.15379}{v} + 0.478802 + 0.236001 \cdot v - 0.064846 \cdot v^{1.5} + 0.004800 \cdot v^2 \qquad \text{(Eq 4.34)}$$

HDGV:

$$m_{HC} = \frac{21.21100}{v} + 14.78801 - 1.317417 \cdot v + 0.238330 \cdot v^{1.5} - 0.012148 \cdot v^2 \qquad \text{(Eq 4.35)}$$

$$m_{CO} = \frac{102.00806}{v} + 231.83615 - 22.37449 \cdot v + 3.896234 \cdot v^{1.5} - 0.182843 \cdot v^2 \quad \text{(Eq 4.36)}$$

$$m_{NOx} = \frac{0.036232}{v} + 4.41308 + 0.049269 \cdot v - 0.000413 \cdot v^{1.5} + 0.00002374 \cdot v^2 \quad \text{(Eq 4.37)}$$

HDDV:

$$m_{HC} = \frac{0.167192}{v} + 6.16352 - 0.437188 \cdot v + 0.070708 \cdot v^{1.5} - 0.003245 \cdot v^2 \quad \text{(Eq 4.38)}$$

$$m_{CO} = \frac{11.76973}{v} + 41.31438 - 3.89797 \cdot v + 0.686019 \cdot v^{1.5} - 0.033310 \cdot v^2 \quad \text{(Eq 4.39)}$$

$$m_{NOx} = \frac{10.14010}{v} + 22.31474 - 0.24921 \cdot v - 0.124332 \cdot v^{1.5} + 0.019711 \cdot v^2 \quad \text{(Eq 4.40)}$$

where

m_{HC} = emission rate of pollutant HC, in gram per mile per vehicle,

m_{CO} = emission rate of pollutant CO, in gram per mile per vehicle,

m_{NOx} = emission rate of pollutant NO_x, in gram per mile per vehicle, and

v = speed, in mph.

iii) Monetary Values of Pollutants

To calculate monetary emission damage values, the total emissions of various pollutants contributing to given air pollutant concentrations are needed. The estimation of absolute levels of air pollutant emissions and air pollutant concentrations is subject to great uncertainties, which affects the accuracy of damage value estimates. To reduce the uncertainty involved in the estimation of absolute levels of emissions and concentrations, many past damage value studies have attempted to estimate damage values for changes in air pollutant concentrations. Yet currently there are no studies that have estimated damage costs by mobile sources; thus, the following estimates are based on stationary sources. Table 4.4 summarizes the damage-based cost estimation by several studies in various areas in the U.S.

The values in Table 4.4 are based on seven studies[16] undertaken in different areas in the U.S. Small's study is based on damage costs to health and materials. The costs associated with

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[16] The studies include:

California Energy Commission. *Electricity Report* (1992).

Haugaard, J. *Measures of Air Pollution Costs Attributable to Motor Vehicles, Technical Report 134* (1981).

mortality are based on lost earnings as a result of death. Small omits the pollutant costs for damage to agriculture. His argument is that the estimates of agriculture damage costs are so small that including them is unwarranted.

Haugaard bases his estimates of pollutant damage costs on damage to human health, materials, and vegetation. Damage costs to human health are based on medical bills and lost earnings as a result of mortality and morbidity. Damage costs to materials are based on 32 kinds of materials affected by pollution. Damage costs to vegetation are based on a study of 77 crops, as well as on shade trees and other ornamental trees and shrubbery.

The purposes of Ottinger's study was to develop a pollutant cost index that could be used for electric utilities in estimating the social costs of producing electricity. Pollutant damages, which are based on impacts to health, materials, vegetation, and visibility, were estimated individually for each pollutant.

As in Ottinger's study, the Massachusetts Department of Public Utilities (MDPU) estimated the damage cost of each pollutant separately. The estimates tend to be among the highest developed values.

The California Energy Commission (CEC) estimated emission values of power plants in order to justify its decision on power plant sittings in 1992. The estimated values are based on the air quality valuation model (AQVM), which includes emission estimation, air quality simulation, estimation of the physical effects of air pollution, and a valuation of air pollution effects. The damage estimates include impacts on human mortality and morbidity, visibility, visual aesthetic effects, material effects, forest-related aesthetic damages, and agricultural effects.

A study completed by the National Economic Research Associates (NERA) for the Nevada Power Company estimated damage values of pollutants, corresponding to southern Nevada. The study included the air pollution effects of human mortality and morbidity, visibility, material and agricultural damages, and acid deposition damages to ecosystems.

The study by Wang uses the emission values estimated in previous original studies (i.e., the CEC study of California air basins, Ottington's study in Massachusetts and New York, etc.) to establish regression relationships between emission values and air pollutant concentration in the atmosphere and total pollution. With the established regression relationships and the data on air pollutant concentrations and population in seventeen U.S. metropolitan areas obtained from EPA, they estimated emission values for these areas. Since their regression relationships rely on original estimates, we suggest that, when available, original emission values should be used for relevant

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Massachusetts Department of Public Utilities. *Investigation by the Department of Public Utilities on Its Own Motion into Proposed Rules to Implement Integrated Resource Management Practice for Electric Companies in the Commonwealth* (1990).

National Economic Research Associates. *External Costs of Electric Utility Resource Selection in Nevada, Final Report* (1993).

Ottinger, R., et al. *Environmental Costs of Electricity* (1990).

Small, K. A. "Estimating the Air Pollution Costs of Transport Modes," *Journal of Transport Economics and Policy* (1977).

Wang, M., Q., et al. *Methods of Valuing Air Pollution and Estimated Monetary Values of Air Pollutants in Various U.S. Regions* (1994).

areas. Therefore, the data for ten non-attainment areas not mentioned in the previous reports are recorded in Table 4.4. Although their method yielded findings not as accurate as the original estimates, the values are superior to the values directly adopted for the region from ad hoc selection of estimates in other regions.

The results of the previous reports that were expressed in dollars other than 1992 dollars were converted into 1992 dollars by using the consumer price index.[17]

The CO damage values based on power plant emissions are implied to be virtually zero among most of the cited studies. CO disperses rapidly and is not a problem at great distances from the source. But while power plants and people are not close together, motor vehicles and people *are* usually close together. Therefore, CO emissions from motor vehicles are far more damaging than those from power plants.

By using the damage value for CO, HC, and NO_X in Table 4.4, we find that the annual pollution cost for passenger cars or trucks on a stretch of roadway $A_{pl}(v_i)$ is

$$A_{pl}(v_i) = \sum_{i=1}^{8}\left(VMT_i \cdot \sum_{p}\left(\gamma_p \cdot m_p(v_i)\right)\right) \qquad \text{(Eq 4.41)}$$

where

p = a pollutant,

i = the ith period as described in the previous section,

γ_p = the damage value for pollutant p, in dollars per gram,

VMT_i = the annual auto or truck VMT on the corridor(s) during ith period,

v_i = the speed in ith period, determined in the previous section, and

$m_p(v_i)$s are as in Eq 4.29 – Eq 4.40, in grams per mile.

4.1.2.3. Incident Delay Cost: One of the most apparent impacts caused by urban congestion is traffic delay. The analysis of delay has been divided into two categories, namely, recurring delay and incident delay. Recurring delay occurs as a result of normal daily operations — increased travel time owing to peak hour demand. This part of delay has been taken care of in the travel time cost, which accounts not only for the recurring delay but for user travel time as well.

Another part of delay related to congestion is incident delay. Incident delay is caused by accidents, breakdowns, or by other occurrences that decrease roadway capacity. Table 4.5 gives the incident delay on expressways and arterials in 50 metropolitan cities. Along with the incident delay, there are daily vehicle miles of travel (DVMT) and number of lanes (Lane) listed in Table 4.5. Delays may be correlated with DVMT. The more DVMT a city has, the more delay the

[17] The Consumer Price Indexes (CPI) are yearly all-item CPI, obtained from Economic Report of the President, Transmitted to the Congress, U.S. Government Printing Office, Washington, D.C., 1994.

travelers experience. The relationship between delay and number of lanes might be tricky. Usually, the number of lanes has a positive correlation with DVMT and in turn has a positive relation with delay. However, when the number of lanes increases to a certain point, the delay may be reduced, since the travelers can use the extra lanes to pass through the incident site.

Table 4.4. Damage values of pollutants ($/kg), 1992 dollars

Area	Study	HC	CO	NO_X	SO_X	PM
Atlanta	Wang	2.433	N/A	4.90	3.078	5.850
Baltimore	Wang	2.501	N/A	5.01	2.964	5.114
Boston	Ottinger	N/A	N/A	2.04	5.069	2.964
California	Small	0.302	0.019	1.00	1.230	0.586
Chicago	Wang	3.055	N/A	6.09	4.073	12.265
Denver	Wang	1.527	N/A	3.21	2.636	3.836
Houston	Wang	4.005	N/A	7.80	3.293	5.872
Iowa	Hauggard	0.367	0.028	1.20	1.482	1.358
Las Vegas	NERA	N/A	N/A	0.24	0.326	1.543
Los Angeles	CEC	7.820	0.003	16.39	8.401	53.880
Massachusetts	MDPU	N/A	1.090	8.10	1.867	4.990
Milwaukee	Wang	2.184	N/A	4.40	2.501	3.349
New Orleans	Wang	2.161	N/A	4.39	2.796	4.073
New York	Ottinger	N/A	N/A	2.04	5.069	2.964
Philadelphia	Wang	3.406	N/A	6.72	3.779	9.459
Sacramento	CEC	4.672	0.001	6.89	1.697	2.464
San Diego	CEC	0.111	0.001	6.29	3.028	16.098
S. F. Area	CEC	0.102	0.001	8.42	3.940	27.605
S. J. Valley	Wang	2.534	N/A	5.08	2.953	7.411
Washington, D.C.	Wang	2.772	N/A	5.54	3.474	7.083

Sources: California Energy Commission. *Electricity Report* (1992).
Haugaard, J. *Measures of Air Pollution Costs Attributable to Motor Vehicles, Technical Report 134* (1981).
Massachusetts Department of Public Utilities. *Investigation by the Department of Public Utilities on Its Own Motion into Proposed Rules to Implement Integrated Resource Management Practice for Electric Companies in the Commonwealth* (1990).
National Economic Research Associates. *External Costs of Electric Utility Resource Selection in Nevada, Final Report* (1993).
Ottinger, R., et al. *Environmental Costs of Electricity* (1990).
Small, K. A. "Estimating the Air Pollution Costs of Transport Modes," *Journal of Transport Economics and Policy* (1977).
Wang, M., Q., et al. *Methods of Valuing Air Pollution and Estimated Monetary Values of Air Pollutants in Various U.S. Regions* (1994).

In order to find the best model to describe the incident delay, some socio-economic characteristics of metropolitan cities are thrown into the model. First, the higher population density could increase congestion, and, in turn, increase the incident delay. Weather conditions are also critical to the delay. Individuals living in cities associated with bad weather conditions may experience more accidents and higher delays, compared with their counterparts having good weather. In order to capture the weather condition, the historical data of rain fall and snow fall in these 50 cities were pulled out. The details of these data, as well as the population densities, are reported in Table 4.6.

Table 4.5 1990 incident delay on expressways and arterials

	Expressway			Arterial		
Urban Area	Delay (veh-hr)	DVMT (1000)	Avg. No. of Lanes	Delay (hr)	DVMT (1000)	Avg. No. of Lanes
Albuquerque, NM	3,160	2,400	5.0	7,670	3,790	3.7
Atlanta, GA	81,160	24,260	6.1	41,320	9,780	3.7
Austin, TX	19,640	5,440	5.6	5,200	2,090	4.2
Baltimore, MD	57,900	15,800	5.4	23,020	9,850	4.1
Boston, MA	214,810	21,610	5.9	31,900	12,540	2.3
Charlotte, NC	3,820	2,300	4.2	13,310	3,090	3.0
Chicago, IL	171,670	38,030	5.7	112,110	29,050	3.7
Cincinnati, OH	14,310	11,380	5.7	5,170	3,670	3.3
Cleveland, OH	12,400	13,700	4.7	9,500	5,790	3.0
Columbus, OH	9,800	8,350	5.8	8,720	3,180	3.3
Corpus Christi, TX	750	1,560	5.4	660	1,500	3.9
Dallas, TX	149,860	23,680	5.9	12,800	8,310	4.8
Denver, CO	36,220	11,270	5.2	32,980	10,900	3.9
Detroit, MI	130,550	22,650	5.8	89,380	22,880	4.4
El Paso, TX	3,910	3,330	5.2	970	3,200	4.2
Fort Worth, TX	54,500	11,840	5.8	6,530	4,240	4.1
Ft. Lauderdale, FL	13,770	7,110	5.4	25,030	5,800	4.3
Hartford, CT	12,290	6,230	5.5	7,130	3,750	3.7
Honolulu, HI	26,720	4,620	5.2	6,090	1,570	3.8
Houston, TX	188,680	28,230	6.3	31,320	10,830	4.3
Indianapolis, IN	6,120	8,050	5.3	3,790	3,970	3.7
Jacksonville, FL	13,410	5,380	4.6	17,520	5,810	3.7
Kansas City, MO	10,000	12,560	4.4	7,820	4,810	3.5
Los Angeles, CA	722,130	110,350	8.2	238,990	80,370	4.0
Louisville, KY	1,940	6,200	4.6	8,870	2,950	3.6

Source: Schrank, D. L., S. M. Turner, and T. J. Lomax. *Estimates of Urban Roadway Congestion — 1990*, Interim Report FHWA/TX-90/1131-5, TTI, 1993.

Table 4.5 1990 incident delay on expressways and arterials (Cont')

	Expressway			Arterial		
Urban Area	Delay (veh-hr)	DVMT (1000)	Avg. No. of Lanes	Delay (hr)	DVMT (1000)	Avg. No. of Lanes
Memphis TN	2,180	4,340	5.4	8,600	4,240	4.3
Miami, FL	48,870	8,570	5.4	78,180	15,810	4.3
Milwaukee, WI	14,230	7,690	5.6	9,400	4,780	3.4
Minn-St. Paul, MN	31,000	17,790	4.9	19,470	5,640	3.3
Nashville, TN	6,900	5,000	4.6	14,390	5,440	3.3
New Orleans, LA	28,830	4,970	5.8	12,580	4,100	4.2
New York, NY	718,780	82,920	5.6	263,200	52,060	3.4
Norfolk, VA	41,450	5,450	4.6	8,720	4,260	3.5
Oklahoma City, OK	3,790	6,940	5.1	7,380	3,590	3.2
Orlando, FL	18,690	5,950	4.9	21,280	3,850	3.7
Philadelphia, PA	54,280	18,330	5.1	102,530	21,390	3.1
Phoenix, AZ	11,770	7,670	5.6	71,430	17,610	4.1
Pittsburgh, PA	30,700	8,200	4.3	40,730	10,910	3.2
Portland, OR	34,300	7,470	5.1	13,750	3,710	3.3
Sacramento, CA	13,490	9,260	6.9	23,790	7,000	4.0
Salt Lake City, UT	2,640	5,330	5.6	4,210	2,040	3.6
San Antonio, TX	26,290	9,280	5.3	4,610	5,240	3.5
San Bernardino-Riv, CA	94,310	14,580	7.1	33,530	10,150	4.2
San Diego, CA	46,770	27,690	7.4	14,610	9,340	3.4
San Fran-Oak, CA	302,210	42,590	6.8	57,560	14,000	3.9
San Jose, CA	88,010	15,780	6.6	32,380	6,780	4.2
Seattle-Everett, WA	116,190	18,920	6.0	32,230	9,130	3.4
St. Louis, MO	26,550	19,120	5.5	44,510	12,960	3.2
Tampa, FL	8,830	3,630	4.9	17,190	4,360	3.8
Washington, DC	236,460	25,340	5.3	109,500	19,560	4.0
Average	-	-	5.526	-	-	3.714

Source: Schrank, D. L., S. M. Turner, and T. J. Lomax. *Estimates of Urban Roadway Congestion — 1990,* Interim Report FHWA/TX-90/1131-5, TTI, 1993.

Table 4.6 Socio-economic characteristics

Urban Area	Density (Person/sq.mi.)	Rain Fall (in)	Snow Fall (in)	Rain Dummy	Snow Dummy
Albuquerque, NM	2,060	8	11	0	0
Atlanta, GA	1,210	48	2	1	0
Austin, TX	1,460	33	1	0	0
Baltimore, MD	3,620	40	22	1	1
Boston, MA	2,760	43	42	1	1
Charlotte, NC	1,880	43	6	1	0
Chicago, IL	3,770	34	40	0	1
Cincinnati, OH	2,000	40	19	1	1
Cleveland, OH	2,780	35	52	1	1
Columbus, OH	2,740	37	28	1	1
Corpus Christi, TX	1,600	29	0	0	0
Dallas, TX	1,380	32	3	0	0
Denver, CO	1,780	16	60	0	1
Detroit, MI	3,190	32	39	0	1
El Paso, TX	2,570	8	5	0	0
Fort Worth, TX	1,410	32	3	0	0
Ft. Lauderdale, FL	2,950	50	0	1	0
Hartford, CT	1,690	43	53	1	1
Honolulu, HI	4,890	23	0	0	0
Houston, TX	1,760	48	0	1	0
Indianapolis, IN	2,150	39	21	1	1
Jacksonville, FL	1,330	54	0	1	0
Kansas City, MO	1,900	37	20	1	1
Los Angeles, CA	5,230	12	0	0	0
Louisville, KY	2,130	43	17	1	1

Source: Boyer, R., and D. Savageau. *Places Rated ALMANAC — Your Guide to Finding the Best Places to Live in North America*, Prentice Hall, New York, 1993.

Table 4.6 Socio-economic characteristics (Cont')

Urban Area	Density (Person/sq.mi.)	Rain Fall (in)	Snow Fall (in)	Rain Dummy	Snow Dummy
Memphis TN	2,020	49	6	1	0
Miami, FL	3,850	60	0	1	0
Milwaukee, WI	2,240	29	45	0	1
Minn-St. Paul, MN	1,970	26	46	0	1
Nashville, TN	1,130	46	11	1	0
New Orleans, LA	3,000	57	0	1	0
New York, NY	5,270	40	29	1	1
Norfolk, VA	1,130	45	7	1	0
Oklahoma City, OK	1,470	31	9	0	0
Orlando, FL	2,070	51	0	1	0
Philadelphia, PA	3,730	40	20	1	1
Phoenix, AZ	1,940	7	0	0	0
Pittsburgh, PA	2,520	36	45	1	1
Portland, OR	2,450	38	7	1	0
Sacramento, CA	3,040	17	0	0	0
Salt Lake City, UT	1,700	15	58	0	1
San Antonio, TX	2,410	28	1	0	0
San Bernadino-Riv, CA	2,390	21	0	0	0
San Diego, CA	3,230	9	0	0	0
San Fran-Oak, CA	4,350	21	0	0	0
San Jose, CA	3,130	21	0	0	0
Seattle-Everett, WA	2,390	39	15	1	0
St. Louis, MO	2,680	36	18	1	1
Tampa, FL	1,570	49	0	1	0
Washington, DC	3,690	39	16	1	1
Average	-	34.2	15.5	-	-

Source: Boyer, R., and D. Savageau. *Places Rated ALMANAC — Your Guide to Finding the Best Places to Live in North America,* Prentice Hall, New York, 1993.

To simplify the input data and to increase the power of the prediction of the model, two extra dummy variables were created. The Rain-Dummy variable is set to 1 if the annual rainfall of the city is greater than the average of the 50 cities; otherwise it is set to 0. A similar arrangement was made for a Snow-Dummy variable.

By using the data in Table 4.5 and Table 4.6, we performed two regressions for expressways and arterials to find the relationship between delay and other variables. The prototype of the regressions is expressed as

$$Y = \alpha_1 + \alpha_2(\text{DVMT}) + \alpha_3(\text{Lane}) + \alpha_4(\text{Density}) + \alpha_5(\text{Rain}) + \alpha_6(\text{Snow}) + u_1 \qquad \text{(Eq 4.42)}$$

for expressways, and

$$Y = \beta_1 + \beta_2(\text{DVMT}) + \beta_3(\text{Lane}) + \beta_4(\text{Density}) + \beta_5(\text{Rain}) + \beta_6(\text{Snow}) + u_2 \qquad \text{(Eq 4.43)}$$

for arterials,

where

Y = incident delay in the metropolitan city, in vehicle-hours per year,

DVMT = total daily VMT on expressway or arterial, in thousands,

Lane = average number of lanes in both directions,

Density = population density, in persons per square mile,

Variable Rain and Snow are dummy variables, and

u_1 and u_2 are error terms.

The coefficients α_i and β_i obtained after running the regression separately for Eq 4.42 and Eq 4.43 are listed in Table 4.7. The statistic analysis of the regression output shows that the delay has an extremely high correlation with the DVMT. This shadows other variables and makes most of them statistically insignificant. The coefficients of DVMT, Density, and Rain have the expected positive sign, which means more DVMT, higher population density, or rainfall above average all generate more delay. The coefficient of Lane for expressways, however, has a negative sign. This is because the expressway has three to four lanes in one direction. The travelers can use the third or fourth lane to pass through the incident site if the incident blocks two lanes, while in such cases the traveler on an arterial must wait for the incident to clear (as most arterials have fewer lanes than expressways). The negative sign of the coefficient of Snow on expressways suggests that travelers on expressways are more careful during snowy weather than their counterparts on arterials.

Table 4.7 Coefficients of regressions

Coefficient	Estimate	t-value	Coefficient	Estimate	t-value
a_1	43666.00	0.698	b_1	-36248.00	-1.605
a_2	7.61	16.232	b_2	3.46	15.491
a_3	-18997.00	-1.723	b_3	3898.26	0.708
a_4	9.87	1.278	b_4	6.14	2.118
a_5	9782.72	0.717	b_5	9084.33	1.893
a_6	-24251.00	-1.805	b_6	4377.69	0.857
Adjusted R^2	0.919		Adjusted R^2	0.911	

Considering the possible correlation in the error term u_1 and u_2, we ran Zellner's seemingly unrelated regression for the above model. Since the results from the Zellner's seemingly unrelated regression don't improve the results in Table 4.7, we conclude that there is almost no correlation in the error term and the coefficients in Table 4.7 are unbiased.

The above equations present incident delay in a metropolitan area, which cannot be directly used in a corridor. However, we were able to find the incident delay rate with respect to VMT in the area from the equations, which are expressed in Eq 4.44 and Eq 4.45 for expressways and arterials, respectively.

$$R_E = \frac{1}{VMT_E}\left[\alpha_1 + \alpha_2\left(\frac{VMT_E}{365{,}000}\right) + \alpha_3(Lane_E) + \alpha_4(Density) + \alpha_5(Rain) + \alpha_6(Snow)\right] \quad \text{(Eq 4.44)}$$

for expressways, and

$$R_A = \frac{1}{VMT_A}\left[\beta_1 + \beta_2\left(\frac{VMT_A}{365{,}000}\right) + \beta_3(Lane_A) + \beta_4(Density) + \beta_5(Rain) + \beta_6(Snow)\right] \quad \text{(Eq 4.45)}$$

for arterials,

where

R_E = incident delay rate on the expressway in the metropolitan area, in vehicle-hours per VMT,

R_A = incident delay rate on the arterial in the metropolitan area, in vehicle-hours per VMT,

VMT_E = the total annual VMT on expressway in the metropolitan area,

VMT_A = the total annual VMT on arterial in the metropolitan area,

$Lane_E$ = average number of lanes of expressway in both directions,

$Lane_A$ = average number of lanes of arterial in both directions,

Density = the population density, in persons per square mile,

Variable Rain and Snow are dummy variables, and

α_i and β_i are as in Table 4.8, for i = 1 - 6.

In MODECOST, the average number of lanes in expressways and arterials in a metropolitan area are defaulted to 5.53 and 3.71,[18] respectively.

After deriving the incident delay rates, the total incident delay on a corridor(s) can be expressed as the product of the incident delay rate and annual VMT on the corridor(s). Then the total cost may be expressed as

$$A_{id} = \alpha \cdot \beta \cdot R \cdot VMT \qquad \text{(Eq 4.46)}$$

where

A_{id} = annual incident delay cost, in dollars per year,

α = the average vehicle occupancy, in passengers per vehicle,

β = the travelers' value of in-vehicle travel time, in dollars per passenger per hour,

R = the incident delay rate, as defined in Eq 4.44 and Eq 4.45, and

VMT = the total annual auto or truck VMT on the corridor.

The suggestion of selection of α and β refers to the earlier sections.

4.1.2.4. Accident Cost Not Covered by Insurance: Accidents are an unavoidable part of transportation. They cause not only delay but also personal injuries and property damage. They occur across all modes and involve substantial expense for those involved and for society as a whole. The delay cost of accidents are covered by the incident delay cost estimation in the previous section. This section mainly deals with the personal injury cost and property damage cost.

Accidents involve expense for medical services, crash clean-up, property damage, etc. Some of the costs overlap with the insurance costs that vehicle owners pay as a part of user costs. Others resulting from injuries or deaths, pain, suffering, and reduced quality of life are more

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18 The figures are derived from the average number of lanes in fifty cities shown in Tables 4-6 and 4-7.

difficult to quantify. The accident costs depend on the severity and frequency of accidents, which are discussed below.

i) Cost of An Accident

One of the factors determining total accident costs is severity of the accidents. Recent research[19] has evaluated the accident cost estimation and presented what appears to be the best available societal cost of vehicle accidents. The principal advantage of the study is its expression of accident costs in a form that can be directly used with state accident data, rather than in terms of the Maximum Abbreviated Injury Scale (0, no injury; 1-5 least to most severe non-fatal injury; 6 fatality). Another advantage is that the costs are expressed on a per-accident basis, instead of on a per-victim or per-vehicle basis. The final conclusion of the study on the different kinds of accidents (fatal or non-fatal) at different locations is summarized in Table 4.8, shown in 1980 dollars. The values have been updated to 1992 dollars in Table 4.9, using the Consumer Price Indexes (CPI) 82.4 in 1980 and 140.3 in 1992.[20]

Table 4.8 Accident cost in 1980 dollars ($/Accident)

	Rural	Urban
Fatal Accident	883,137	826,856
Non-Fatal Accident	10,644	8,745

Source: Rollins, J. B. and W. F. McFarland. "Costs of Motor Vehicle Accidents and Injuries," *Transportation Research Record, 1068,* 1988.

Table 4.9 Accident cost in 1992 dollars ($/Accident)

	Rural	Urban
Fatal Accident	1,503,691	1,407,863
Non-Fatal Accident	18,123	14,890

Source: Rollins, J. B. and W. F. McFarland. "Costs of Motor Vehicle Accidents and Injuries," *Transportation Research Record, 1068*, 1988.
Economic Report of the President, Transmitted to the Congress, U.S. Government Printing Office, Washington, D.C., 1994.

The rates in Table 4.10 are average values. The rate of any particular accident varies depending on the conditions of travel. Vehicle accidents occurring in congested urban areas

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19 Rollins, J. B. and W. F. McFarland. "Costs of Motor Vehicle Accidents and Injuries," *Transportation Research Record, 1068*, 1988.

20 The Consumer Price Indexes (CPI) are yearly all-item CPI.

usually are less costly than those on rural freeways, where cars are traveling faster and crashes are more serious.

ii) Accident Frequency

The next step is to find the frequency of accidents (i.e., how often an accident takes place). Some social econometrists[21, 22, 23] have reported that the frequency of accidents is related to the speed variation and to other socio-economic factors (e.g., minimum legal drinking age, income, etc.). However, their models are very poor, which is reflected by very low correlation coefficient R^2, and statistically insignificant estimates (low t-ratio). The fatality and injury risk should have a very high correlation with miles driven, or VMT. Using the accident occurring rates and corresponding VMT[24] in 50 states, we found a simple relation between accident occurring rates and VMT. The basic linear regression model is assumed to be

$$\text{No. of Accidents} = \chi \cdot \text{VMT} \cdot 10^{-6} \qquad \text{(Eq 4.47)}$$

The regression results of χ are listed in Table 4.10.

Table 4.10 Frequency of accidents in urban areas

Coefficient	Fatal		Non-Fatal	
	Estimate	t-value	Estimate	t-value
χ	0.01140	44.79	1.0950	31.32
Adjusted R^2	0.94		0.90	

The extremely high t-ratios show a strong correlation between number of accidents and VMT traveled. The high R^2 shows a good fit to the data.

iii) Accident Costs Not Covered by Insurance

As mentioned in the first report, part of the accident cost is covered by insurance paid by the users, which will be accounted for in the user cost. In order not to double count the costs covered by the insurance, it is necessary to identify what percentage of the accident costs are covered by the insurance. Few studies have been undertaken in this area. In an Urban Institute

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21 Lave, C. A. "Speeding, Coordination, and the 55 MPH Limit," *American Economic Review, Vol. 75*, 1985.

22 Levy, D. T. and P. Asch. "Speeding, Coordination, and the 55-MPH Limit: Comment," *American Economic Review, Vol. 79*, 1989.

23 Snyder, D. "Speeding, Coordination, and the 55-MPH Limit: Comment," *American Economic Review, Vol. 79*, 1989.

24 *Highway Statistics* (1992).

study,[25] the authors mentioned that about 68 percent was paid by the general public, and the remainder was paid by the people involved in the accident and their families. Faigin,[26] in her study of cost of injury, pointed out that private sources, primarily in the form of automobile insurance and worker's compensation, account for 73 percent of the total payments, leaving the remaining 27 percent paid by public. In this study, we assume that 70 percent of the costs are paid by insurance, while the remaining 30 percent are paid by users. Therefore, the accident costs (not covered by insurance) are expressed as

$$A_a = 0.00971 \cdot VMT \qquad \text{(Eq 4.48)}$$

where

A_a = annual total accident costs not covered by insurance, in dollars per year, and

VMT = the total annual personal or commercial VMT on the corridor(s).

4.1.2.5. Other External Costs: As reported in the first report, in addition to travel time cost, air pollution cost, incident delay cost, and accident cost, the external costs include such other categories as water pollution cost, land loss cost, and noise. Unfortunately, further study and modeling of these costs are beyond the scope of this research. In order not to overlook these costs in the total cost, we use the national average value shown in Table 4.11. Users of MODECOST can either input their own values or the national average to account for these externalities. The costs are based on cents per person mile of travel (PMT). Details are provided in a previous report.

Table 4.11 Other externalities by category (in ¢ per PMT)

Externality	Brief	Cost
Local Government	Costs not counted for in facility cost.	0.26
Noise	Costs due to noise.	0.15
Building Damage	Damage caused by vibration in buildings.	0.01
Loss of Aesthetics	Aesthetic damage by transportation.	-
Water Pollution	Water pollution and oil spills.	0.13
Weather Change	Damage of global warming by CO_2 emission.	2.00 - 3.50
Wetlands	Wetland loss due to roadway construction.	-
Proper Values	Negative impact on land by traffic artery.	-
Land Loss	Land loss related to automobile.	-
Energy Security	Cost of uncertainty of energy market.	1.50 - 5.00

Source: Miller, P., and J. Moffet. *The Price of Mobility — Uncovering the Hidden Costs of Transportation*, Natural Resources Defense Council, 1993.
Missing data are primarily due to the lack of quantitative studies in those areas.

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25 Urban Institute. *The Costs of Highway Crashes*, Prepared for FHWA, 1991.

26 Faigin, B. M. "The Costs of Motor Vehicle Injuries," *Auto & Traffic Safety*, 1991.

4.1.2.6. Annualized Total External Costs: It is worth noting that the previous descriptions of the calculations of external cost are on an annual basis. During the lifetime of a roadway facility, there are variations in annual traffic volumes as well as annual VMT, and, in turn, there are variations in annual external costs during different years. In order to capture the life-cycle concept, we use annualized external costs as our criteria in calculating total cost. This is demonstrated in Figure 4.5. Or mathematically

$$A_{ex} = \left(\sum_{t=0}^{T} \left(A_{ex}^{t} \cdot (P/F, i, t) \right) \right) \cdot (A/P, i, T) \qquad \text{(Eq 4.49)}$$

where

A_{ex} = annualized external cost, in dollars per year,

A_{ex}^{t} = total annual external costs — including costs of travel time, air pollution, incident delay, accident, and others — in year t, in dollars per year,

i = discount rate, and

T = lifetime of roadway facility, in years.

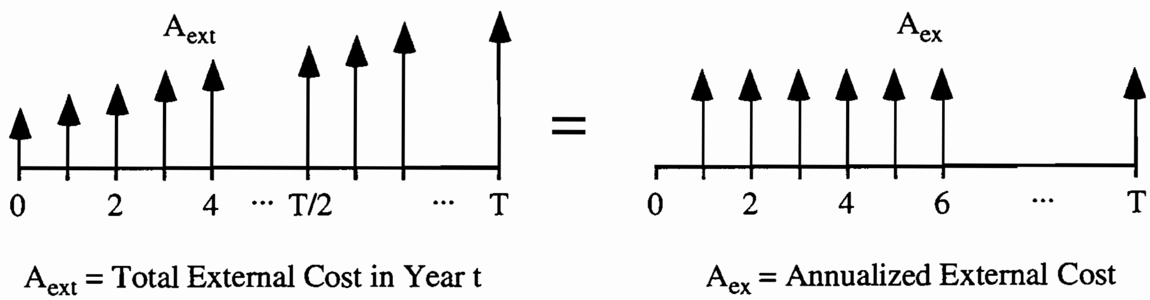
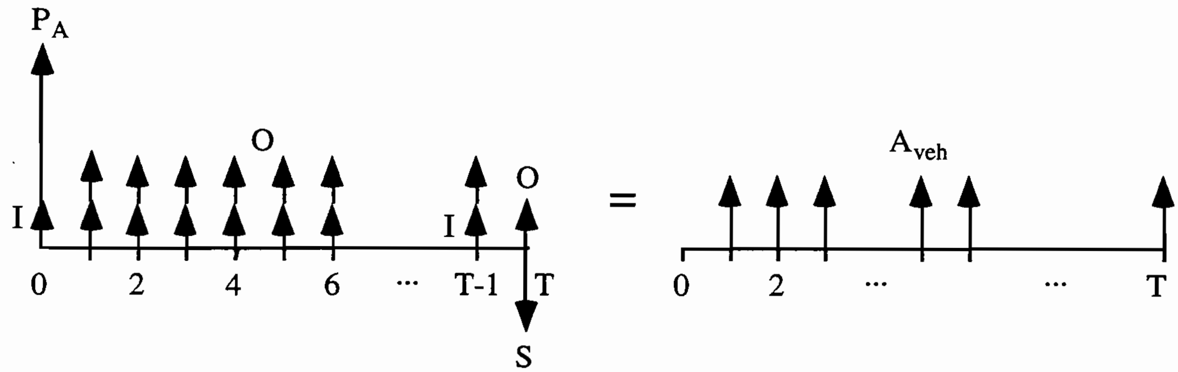


Figure 4.5 Cash-flow diagram of annualized external cost

4.1.3. Personal Vehicle Cost

As noted earlier, personal vehicles include all passenger cars and those pick-up trucks used for personal travel purposes. In MODECOST, the percentage of pick-up trucks and minivans used for personal transportation is one of the user inputs. Vehicle costs and operating costs will be discussed in this section.

Many personal vehicle owners may think of their costs only in terms of outlays for fuel, oil, tires, and tolls. A more careful examination shows that some costs occur whether or not the vehicle is driven, while others are directly related to the amount of travel. This travel-related group is generally referred to as operating costs, and the other group as ownership costs. Some of the costs are incurred once in the auto life (i.e., initial capital cost), while others occur on an annual basis. The cash-flow diagram of life-cycle user cost is shown in Figure 4.6. The details are explained below.



P_A = Initial Price; I = Insurance Cost;
O = Operating Cost; S = Salvage Value;
T = Vehicle Life.

Figure 4.6 Cash-flow diagram of user cost

4.1.3.1. Ownership Costs: Ownership costs include depreciation, finance charges, insurance, registration and title fees, and any taxes applied to these items. Since registration and titling fees as well as taxes are collected for the purpose of constructing and maintaining the current roadway system, they are excluded from the ownership costs to avoid double counting.

i) Depreciation and Finance Charges

Depreciation is the loss of value of the vehicle during its lifetime owing to the passage of time, mechanical and cosmetic failings, and the number of miles it is driven. Depreciation rates drop sharply during the first few years of an auto's life, and much more gradually after that. Since there is no clear pattern, only the lifetime average depreciation is considered in our study.

Finance charges are based on a typical loan rate, finance term, and percentage of down payment. Since a number of options are available, MODECOST allows users to approximate their own costs with relative ease. Most vehicle owners either pay interest on money they borrow to buy their vehicles, or they forego interest they would have earned if they opt to use savings or other investments to pay for the vehicles outright.

Using the engineering economic concepts introduced in Chapter 3, and considering the salvage value at the end of the lifetime, we can express the annual depreciation and finance charge as

$$A_D = \left[P_A \cdot (1-p) + P_A \cdot p \cdot (A/P, r, t_r) \cdot (P/A, i, t_r)\right] \cdot (A/P, i, T) - S \cdot (A/F, i, T) \qquad \text{(Eq 4.50)}$$

where

A_D = the annual depreciation and finance charge, in dollars per vehicle per year,

P_A = personal vehicle purchase price, in dollars per vehicle,

p = the financed part of the purchase price,

r = loan rate,

t_r = loan period, in years,

i = discount rate,

T = auto life time, in years, and

S = salvage value, in dollars per vehicle.

ii) Insurance Cost

Insurance cost is determined by a number of factors, including vehicle type, the amount and type of coverage selected, the user's driving record and age, and the region in which the vehicle is used. Only the average insurance cost is considered in this study. Since the insurance is paid as soon as the car is bought, it is necessary to include the interest earned in a 1-year period. Mathematically, the annualized insurance cost is

$$A_I = I \cdot (F / P, i, 1) \qquad \text{(Eq 4.51)}$$

where

A_I = the annualized insurance cost, in dollars per vehicle,

I = Insurance paid by the user, in dollars per vehicle,

i = discount rate.

4.1.3.2. Operating Costs: Operating costs are those annual expenditures made throughout the vehicle's life. They include gasoline cost, tire change cost, oil change cost, scheduled and unscheduled maintenance cost, and parking cost. The majority of these costs are functions of vehicle usage and vehicle age. In this study, we consider only the annualized operating costs over a vehicle's lifetime.

i) Gasoline Cost

Gasoline cost is a major expenditure for vehicles of all sizes. These costs depend not only on the vehicle's engine size, but also on user driving patterns and vehicle usage. For the sake of simplicity, it is assumed that the average gas mileage of autos is 21 miles per gallon.[27] The annual gas cost is then

$$A_{gas} = \frac{\text{Annual Mileage}}{21.0} \cdot P_{gas} \qquad \text{(Eq 4.52)}$$

where

A_{gas} = the annual gas cost, in dollars per vehicle,

Annual Mileage = the annual miles driven, in miles per vehicle, and

P_{gas} = the price of gasoline without taxes, in dollars per gallon.

ii) Tire Cost

In practice, the timing of replacing year will depend on the tire replacement schedule actually followed. The default value given in Table 4.12 is annualized cost based on the cost of replacing tires at years 4, 7, 12.[28]

iii) Oil Cost

Oil costs for a new or relatively new vehicle are mainly dependent on the car manufacturer's instructions for oil changes. The value in Table 4.12 is based on a 7,500-mile interval for all vehicles.

iv) Maintenance Cost

Maintenance cost includes scheduled maintenance, unscheduled maintenance, and enhanced I/M. Scheduled maintenance is based on the estimation shown in owner's manual. Generally, the suggested maintenance service includes maintenance of the cooling system, oil changes, safety checks, tune-ups, and lubrication. The unscheduled maintenance shown in Table 4.12 was estimated by obtaining data on the total costs for repairs and maintenance, adjusting for differences across vehicle classes, and subtracting the cost of scheduled repairs and maintenance. The enhanced I/M is the cost of inspection and maintenance, two items that are required by most states.[29]

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27 *Highway Statistics* (1992).

28 The value is from *Cost of Owning & Operating Automobiles, Vans & Light Trucks 1991*, U.S. Department of Transportation, Washington, D.C., 1992. The number of replacement tires is based on a life expectancy of 64,000 km (40,000 miles) for radial tires. During the life of the vehicle, twelve new radial tires are purchased.

29 The data are from *Cost of Owning & Operating Automobiles, Vans & Light Trucks 1991*, (1992). See the report for details.

v) Parking Cost

The parking cost varies from area to area. In most congested cities, it is extremely high, while in small cities it is relatively low. Overall, the operating cost may be expressed as

$$A_O = A_{gas} + A_{tire} + A_{oil} + A_{main} + A_{park} \qquad \text{(Eq 4.53)}$$

where

A_O = annual operating cost, in dollars per vehicle,

A_{gas} = annual gas cost, in dollars per vehicle,

A_{tire} = annual tire cost, in dollars per vehicle,

A_{oil} = annual oil cost, in dollars per vehicle,

A_{main} = annual maintenance, in dollars per vehicle, and

A_{park} = annual parking cost, in dollars per vehicle.

Therefore, the total user cost on a dollars-per-year basis may be expressed as

$$A_{user} = \frac{A_P + A_I + A_O}{\text{Annual Mileage}} \cdot \text{VMT} \qquad \text{(Eq 4.54)}$$

where

A_P, A_I, and A_O are as described in Eq 4.50, Eq 4.51, and Eq 4.52,

Annual Mileage = annual miles driven by a vehicle, in miles per vehicle, and

VMT = the total annual personal vehicle VMT on the corridor in a given year.

The following table (Table 4.12) gives default values used to calculate user cost. These values are based on a national average, and thus may not be appropriate in some areas. Users can replace any of these values in MODECOST to find the cost value for any given scenario.

Table 4.12 Default values for user cost

Item	Symbol	Unit	Default Value
Vehicle Price	P_A	$ per vehicle	12,707
Percent Financed	p	-	0.75
Loan Rate	r	-	10.50 percent
Loan Period	t_r	Year	4
Vehicle Life	t_l	Year	12
Salvage Value	S	$ per vehicle	514
Insurance Paid by User	I	$ per vehicle per year	755
Annual Mileage	-	Miles per vehicle per year	10,700
Gas Price	P_{gas}	$ per gallon	0.686
Annual Tire Cost	A_{tire}	$ per vehicle per year	97
Annual Oil Cost	A_{oil}	$ per vehicle per year	59
Annual Maintenance	A_{main}	$ per vehicle per year	482
Scheduled	-	$ per vehicle per year	232
Unscheduled	-	$ per vehicle per year	195
I/M	-	$ per vehicle per year	55

Source: *Cost of Owning & Operating Automobiles, Vans & Light Trucks 1991*, U.S. Department of Transportation, Washington, D.C., 1992.
The annual tire, oil, and maintenance costs are annualized from the periodic costs in the report.
Annual mileage is the average of total mileage over the vehicle lifetime.

4.1.3.3. Annualized User Cost: Owing to the variations in annual traffic volumes, as well as in annual VMT, the user cost for a different year could be different. In this report, we use the annualized life-cycle cost concept as our criteria in calculating total cost. The annualized user cost can be expressed as

$$A_{user} = \left(\sum_{t=0}^{T} \left(A_{user}^{t} \cdot (P/F, i, t) \right) \right) \cdot (A/P, i, T) \qquad \text{(Eq 4.55)}$$

where

A_{user} = annualized user cost, in dollars per year,

A_{user}^{t} = total user cost in year t, in dollars per year,

i = discount rate, and

T = lifetime of roadway facility, in year.

4.2. BUS USER COST

The following sections provide quantitative information on the full costs for bus users.

4.2.1. Roadway Facility Cost

Almost all transit buses share the same roadway facilities as auto users. The information on roadway facility estimation is summarized in section 4.1.1, "Facility Cost Estimation."

4.2.2. External Cost

As shown in the previous chapter, bus users bear the same kinds of external costs as auto users. The following gives their monetary values.

4.2.2.1. Travel Time Cost by Bus Users: In general, bus users require more time to make a trip. The travel time by bus users is related to not only bus travel speed, but also to waiting time at the bus stop and to walking time from origin to stop and from stop to destination.

i) In-Vehicle Time

The in-vehicle time is the total time spent by a user traveling from an origin bus stop to a destination bus stop. This time includes bus running time, stopping time at stops, etc.

The basic model is based on the above relation: travel time is equal to the running time plus the time incurred in picking up or discharging passengers. Thus, the in-vehicle time over a 1-mile segment can be expressed as

$$T_{B-in} = \frac{1}{v_B} + t_a \cdot N_p \cdot N_S \qquad \text{(Eq 4.56)}$$

where

$T_{B\text{-}in}$ = in-vehicle time by bus, in hours per mile,

v_B = average bus speed, in mph,

t_a = boarding or alighting time of one passenger at a bus stop, in hours per passenger,

N_p = average volume of passenger alighting and/or boarding at a bus stop, and

N_S = number of bus stops in a one-mile segment.

The boarding time appears to be somewhat greater than alighting time, as the passengers have to pay fares. For the current situation, it is assumed that regardless of the type of payment, the boarding or alighting time, t_a, is 3.0 seconds per passenger, and a constant boarding and alighting volume of 4 passengers per stop.

The difficulty in implementing this model arises from the fact that the running speed of the bus, v_B, is depend upon many factors. Besides the type of engines used, bus running speeds are a function of v/c ratio, traffic signalization, etc.

In order to obtain an average bus speed, v_B, it is assumed that the average car speed in prevailing traffic conditions is the maximum speed a bus can attain and that the bus stop spacing is large enough for buses to reach this maximum speed,[30] or

$$v_B = \frac{1}{\dfrac{1}{v_{car}} + \dfrac{v_{car}}{3600 \cdot S \cdot a}} \tag{Eq 4.57}$$

where

v_B = average bus speed, in mph,

v_{car} = average car speed, in mph,

S = average distance between bus stops, in miles, and

a = bus acceleration/deceleration rate, assumed as 2 mphps.

Substituting Eq 4.57 for Eq 4.56 yields

$$\begin{aligned} T_{B-in} &= \frac{1}{v_{car}} + \frac{v_{car}}{7200 \cdot S} + \frac{12}{3600} \cdot N_S \\ &= T_{car} + \frac{1}{7200 \cdot S \cdot T_{car}} + \frac{12}{3600} \cdot N_S \end{aligned} \tag{Eq 4.58}$$

where

$T_{B\text{-}in}$ = average in-vehicle time by a bus user, in hours per mile,

T_{car} = average travel time by car over 1 1.61-km (1-mile) segment, in hours per mile, determined by Eq 4.21, Eq 4.22, or Eq 4.24 according to different traffic conditions, and

N_S = number of bus stops in a mile.

ii) Out-of-Vehicle Time

The out-of-vehicle time by a bus traveler includes time spent at the bus stop waiting for a bus, and the time spent walking from an origin to a bus stop and from a stop to a destination. In MODECOST, the waiting time at bus stops is defaulted to one-half the bus headway.[31] Thus, the out-of-vehicle time can be expressed as

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30 Talvitie, A., and Y. Dehghani. "Models for Transportation Level of Service," *Transportation Research, Vol. 14-B*, 1980.

31 Larson, R. C., and A. R. Odoni. *Urban Operations Research*, Prentice-Hall Inc., NJ, 1981.

$$T_{B-out} = T_{o-s} + \frac{1}{2} T_H + T_{s-d} \tag{Eq 4.59}$$

where

$T_{B\text{-}out}$ = average out-of-vehicle time by a bus user, in hours per trip,

$T_{o\text{-}s}$ = average time from origin to bus stop, in hours per trip,

T_H = average bus headway, in hours, and

$T_{s\text{-}d}$ = average time from bus stop to destination, in hours per trip.

iii) Total Travel Time Cost by Bus Users

Here we adopted an approach similar to that used for auto users. A work day or any day of the weekend is divided into four periods — morning peak period, afternoon peak period, day, and night — to capture the traffic variations. The annual total travel time costs by bus travelers are expressed as

$$A_{B-time} = \phi \cdot \beta \cdot \sum_{i=1}^{8} \left(\left(T_{B-in} + \frac{T_{B-out}}{L_{trip}} \right)_i \cdot VMT_{iB} \right) \tag{Eq 4.60}$$

where

$A_{B\text{-}time}$ = total travel time cost by bus users, in dollars per year,

ϕ = the average bus occupancy, in passengers per vehicle,

β = the travelers' value of time, in dollars per passenger per hour,

$T_{B\text{-}in}$ = average in-vehicle time by a bus user, in hours per mile,

$T_{B\text{-}out}$ = average out-of-vehicle time by a bus user, in hours per trip,

L_{trip} = average trip length by a bus traveler, in miles per trip,

VMT_{iB} = the annual bus VMT on the corridor during the ith period, and

i = the ith period, namely morning peak, afternoon peak, day, and night.

4.2.2.2. Air Pollution Cost by Buses: As formulated in Eq 4.61 – Eq 4.63, the emission rates of buses are:

$$m_{HC} = \frac{0.167192}{v} + 6.16352 - 0.437188 \cdot v + 0.070708 \cdot v^{1.5} - 0.003245 \cdot v^2 \tag{Eq 4.61}$$

$$m_{CO} = \frac{11.76973}{v} + 41.31438 - 3.89797 \cdot v + 0.686019 \cdot v^{1.5} - 0.033310 \cdot v^2 \qquad \text{(Eq 4.62)}$$

$$m_{NOx} = \frac{10.14010}{v} + 22.31474 - 0.24921 \cdot v - 0.124332 \cdot v^{1.5} + 0.019711 \cdot v^2 \qquad \text{(Eq 4.63)}$$

By applying the monetary values of pollutants CO, HC, and NO_x in Table 4.4, we get the annual pollution costs for buses as

$$A_{B-pl}\left(\frac{1}{T_{B-in}}\right) = \sum_{i=1}^{8}\left(VMT_{iB} \cdot \sum_{p}\left(\gamma_p \cdot m_p\left(\frac{1}{T_{B-in}}\right)\right)\right) \qquad \text{(Eq 4.64)}$$

where

p = a pollutant,

i = the ith period as described in the previous section,

γ_p = the damage value for pollutant p, in dollars per gram,

VMT_{iB} = the annual bus VMT on the corridor during ith period,

$T_{B\text{-}in}$ = bus in-vehicle time in ith period, determined in the previous section, and

$m_p(v_i)$s are as in Eq 4.61 – Eq 4.63, in grams per mile.

4.2.2.3. Incident Delay Cost by Bus Users: As buses share the same roadway facility with autos and trucks, bus users bear both recurring delays and incident delays. The total costs resulting from incident delays can be expressed as

$$A_{B-id} = \phi \cdot \beta \cdot R \cdot VMT_B \qquad \text{(Eq 4.65)}$$

where

$A_{B\text{-}id}$ = annual incident delay cost, in dollars per year,

ϕ = the average bus occupancy, in passengers per vehicle,

β = the travelers' value of in-vehicle travel time, in dollars per passenger per hour,

R = the incident delay rates on expressways or arterials, as in Eq 4.44 and Eq 4.45, and

VMT_B is the total annual bus VMT on the corridor.

4.2.2.4. Accident Cost Not Covered by Insurance: Bus travelers are safer than auto users. Most bus operators are professional drivers rarely responsible for accidents. In addition, most bus operating agencies have very rigorous safety rules. Thus, we assume that the accident cost not covered by insurance is zero in this study.

4.2.2.5. Other External Costs: The following external costs, the study of which is beyond the scope of this project, are defaulted in MODECOST. Details are provided in a previous report.

Table 4.13 Other externalities (in ¢ per bus PMT)

Externality	Brief	Cost
Local Government	Costs not counted for in facility cost	0.13
Noise	Costs due to noise	0.05 - 0.10
Building Damage	Damage caused by vibration in buildings	-
Loss of Aesthetics	Aesthetic damage by transportation	-
Water Pollution	Water pollution and oil spills	-
Weather Change	Damage of global warming by CO_2 emission	-
Wetlands	Wetland loss due to roadway construction	-
Proper Values	Negative impact on land by traffic artery	-
Land Loss	Land loss related to automobile	-
Energy Security	Cost of uncertainty of energy market	0.85 - 2.8

Source: Miller, P., and J. Moffet. *The Price of Mobility — Uncovering the Hidden Costs of Transportation*, Natural Resources Defense Council, 1993.
Missing data are primarily due to the lack of quantitative studies in those areas, and are assumed as zero in MODECOST.

4.2.2.6. Annualized Total External Costs by Bus Users: As described earlier, the variations in annual traffic volumes, as well as in annual VMT, result in the variations in annual external costs occurring over the life-cycle of a facility. In order to capture the life-cycle concept, we use annualized external cost as our criterion in calculating total cost. This is expressed as

$$A_{B-ex} = \left(\sum_{t=0}^{T} \left(A_{B-ex}^{t} \cdot (P/F, i, t) \right) \right) \cdot (A/P, i, T) \qquad \text{(Eq 4.66)}$$

where

A_{B-ex} = annualized external cost, in dollars per year,

A_{B-ex}^{t} = total annual external costs — including costs of travel time, air pollution, incident delay, and others — in year t, in dollars per year,

i = discount rate, and

T = lifetime of roadway facility, in years.

4.2.3. Bus Agency Costs

The costs incurred by bus agencies include vehicle purchase and overhaul costs, station construction and rehabilitation costs, routine maintenance costs, transit agency operating costs, and administration costs.

4.2.3.1. Vehicle Cost: The cash-flow diagram of the life-cycle bus vehicle cost is shown in Figure 4.7. We assume a major overhaul during the lifetime of the vehicle. Applying engineering economic concepts described in the previous chapter, and considering the financial charge during the loan period, we can express the annualized bus vehicle cost (including both purchase and overhaul) as:

$$\begin{aligned} A_{B-V} = N_B \cdot \big[& P_I \cdot (A/P, r, t_r) \cdot (P/A, i, t_r) \cdot (A/P, i, T) + \\ & P_R \cdot (A/F, i, T_R) \cdot (A/P, i, T) - S \cdot (A/F, i, T) \big] \end{aligned} \qquad \text{(Eq 4.67)}$$

where

A_{B-V} = the annual cost of bus vehicles, in dollars per year,
N_B = number of buses operated on the corridor,
P_I = initial purchase price, in dollars per vehicle,
r = loan rate,
t_r = loan period, in years,
i = discount rate,
T = bus vehicle lifetime, in years,
P_R = overhaul cost, in dollars per vehicle,
T_R = overhaul schedule, in years, and
S = salvage value, in dollars per vehicle.

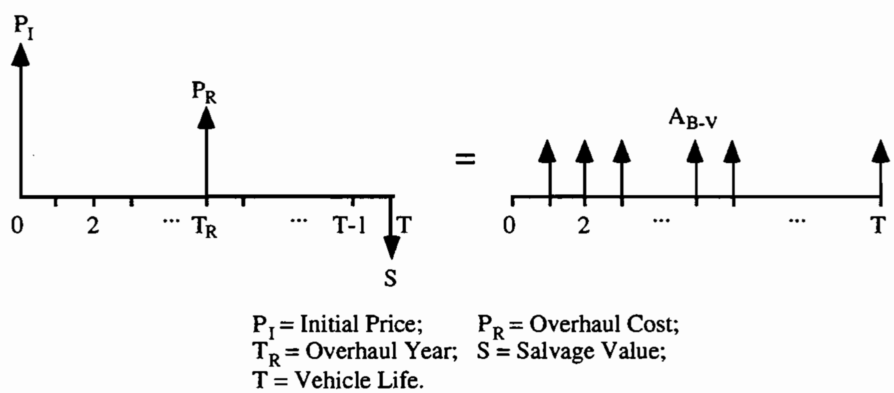
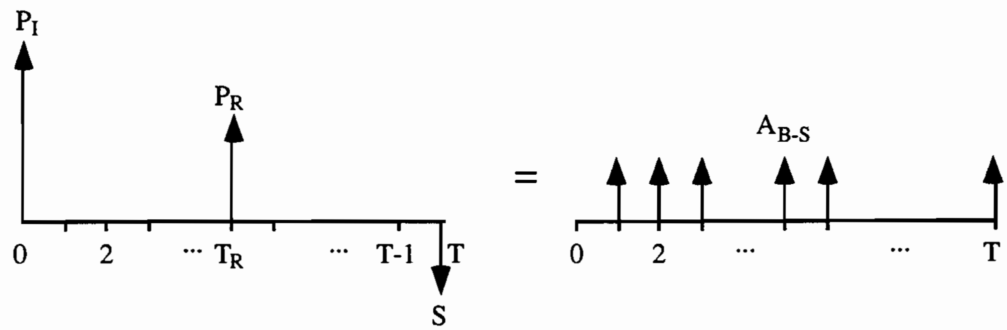


Figure 4.7 Cash-flow diagram of bus vehicle cost

4.2.3.2. Bus Station Cost: Transit buses often require intermediate stops on routes to receive and discharge passengers. Although these stops may reduce bus operating speeds, they are essential in providing desired service levels and in optimizing bus patronage.

There are several types of bus stations considered in our study. Transit centers are terminals that consolidate bus operations at a single location, facilitate passenger interchange between bus lines, reduce bus journey times, and improve general traffic flow by reducing inefficient bus mileage on congested downtown streets. They can achieve substantial time savings for riders, as compared with on-street distribution. Park-and-ride lots serve as a collection point for private vehicle users transferring to transit buses. The size of park-and-ride lots varies widely — from only a few spaces in sparsely populated or less heavily-traveled corridors to many hundreds of spaces serving major rapid transit lines. Shelters, consisting of a bench, an overhead canopy, and a concrete foundation, etc., are frequently used for bus stops.

Figure 4.8 presents a cash-flow diagram of the life-cycle costs of a bus station. We assume a major rehabilitation during the lifetime of a transit center and park-and-ride lot. There is only routine maintenance used for shelters, which will be accounted for in the operating cost.



P_I = Initial Capital Cost; P_R = Rehabilitation Cost;
T_R = Rehabilitation Year; S = Salvage Value;
T = Station Life.

Figure 4.8 Cash-flow diagram of bus station cost

Mathematically, the annualized costs of all stations are

$$A_{B-S} = \sum_{j=1}^{3} \Big\{ N_j \cdot \Big[P_{Ij} \cdot (A/P, r, t_r) \cdot (P/A, i, t_r) \cdot (A/P, i, T_j) + P_{Rj} \cdot (P/F, i, T_{Rj}) \cdot (A/P, i, T_j) - S_j \cdot (A/F, i, T_j) \Big] \Big\} \qquad \text{(Eq 4.68)}$$

where

$A_{B\text{-}S}$ = the annual cost of bus stations, in dollars per year,

j = type of stations, 1 for transit center, 2 for park-and-ride lots, and 3 for shelter,
N_j = number type j stations,
P_{Ij} = initial construction cost of type j station, in dollars per station,
r = loan rate,
t_r = loan period, in years,
i = discount rate,
T_j = lifetime of type j station, in years,
P_{Rj} = rehabilitation cost for type j station, in dollars per station,
T_{Rj} = rehabilitation year for type j station, in years, and
S_j = salvage value of type j station, in dollars per station.

4.2.3.3. Operating Cost: Transit agency operating costs include operating and maintenance costs and administration costs. The costs are flexible and depend on the scale of the transit agency. The administration cost involves engineering staffs and labor costs.

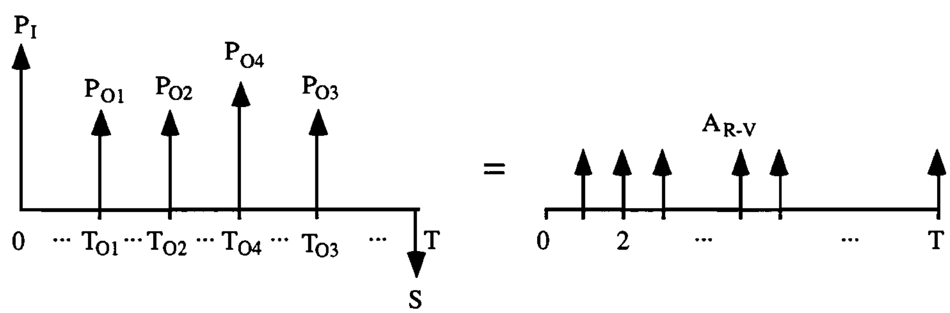
4.3. RAIL USER COST

The following sections present the cash-flow accounting process used in MODECOST.

4.3.1. Facility Cost

The rail facility includes cars, guideways, stations, right-of-way, and yards and shops, etc. The costs involve initial capital costs, overhaul costs, and financial charges.

4.3.1.1. Car Cost: The capital costs of a rail car, including rehabilitation or procurement contract, ancillary and financing, and major and minor overhaul costs, are estimated in determining total life-cycle cost. Annual maintenance and operating costs are estimated in another cost category. The basic cash-flow diagram is shown in Figure 4.9.



P_I = Initial Capital Cost; S = Salvage Value; T = Vehicle Life;
P_{O1} = 1st Minor Overhaul Cost; T_{O1} = 1st Minor Overhaul Schedule;
P_{O2} = 2nd Minor Overhaul Cost; T_{O2} = 2nd Minor Overhaul Schedule;
P_{O3} = 3rd Minor Overhaul Cost; T_{O3} = 3rd Minor Overhaul Schedule;
P_{O4} = Major Overhaul Cost; T_{O4} = Major Overhaul Schedule.

Figure 4.9 Cash-flow diagram of rail car cost

The initial capital cost represents the payment to a car builder or rehabilitation contractor for labor, materials, transportation, and spare parts. Ancillary costs include contract monitoring and testing. Major and minor overhauls are performed on a periodic basis to restore car reliability and reduce routine maintenance costs. Major overhaul includes replacement of batteries, floor covering, propulsion control, seats, doors, air-conditioning systems, brake systems, wiring systems, and communication systems. Minor overhaul involves propulsion overhaul, brake overhaul, car body overhaul, replacement of batteries, and communication systems. The objective of overhauls would not be to lower the rate of increase in operations and maintenance costs, but rather to "rejuvenate" the car. A total of three minor overhauls and one major overhaul are assumed for each of the car fleets, according to a schedule year of a car's life as shown in Figure 4.9. The annualized life-cycle cost of cars are:

$$A_{R-V} = N_V \cdot \Big[P_I \cdot (A/P, r, t_r) \cdot (P/A, i, t_r) \cdot (A/P, i, T) + \sum_{j=1}^{4} P_{Oj} \cdot (P/F, i, T_{Oj}) \cdot (A/P, i, T) - S \cdot (A/F, i, T) \Big] \qquad \text{(Eq 4.69)}$$

where

A_{R-V} = the annual cost of rail cars, in dollars per year,

N_V = number of cars,

P_{Ij} = initial capital cost of a car, in dollars per car,

r = loan rate,

t_r = loan period, in years,

i = discount rate,

T = lifetime of cars, in years,

P_{Oj} = the jth overhaul cost, in dollars per car,

T_{Oj} = the jth overhaul schedule, in years, and

S = salvage value, in dollars per car.

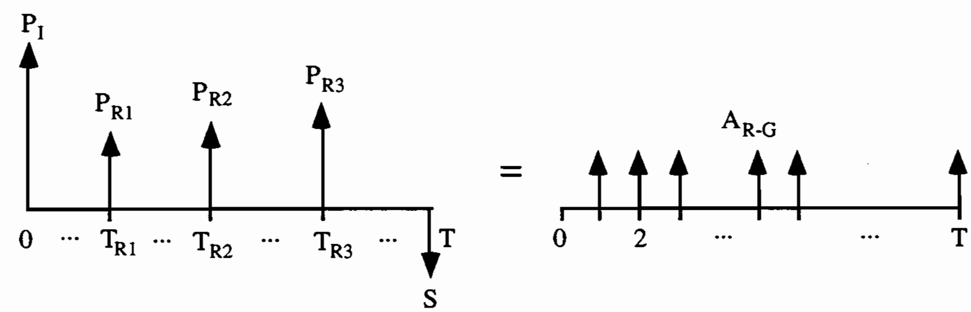
The number of cars operated by a transit agency depends on the speed of the vehicle, headway, standing time at stations, etc. It is estimated in Eq 4.79. Table 4.14 gives the national average subtracted from some figures obtained from the literature.

Table 4.14 Default values for rail car cost (1992 dollars)

Item	Symbol	Unit	Default Value
Initial Cost of A Car	P_I	$ per car	1,244,738
Car Life	T	years	40
Salvage Value	S	$ per car	N/A
Minor Overhaul Cost	P_{O1} - P_{O3}	$ per car	176,079
1st Minor Overhaul Schedule	T_{O1}	years	7
2nd Minor Overhaul Schedule	T_{O2}	years	14
3rd Minor Overhaul Schedule	T_{O3}	years	28
Major Overhaul Cost	P_{O4}	$ per car	457,806
Major Overhaul Schedule	T_{O4}	years	21

Source: Booz-Allen & Hamilton, Inc. *Light Rail Transit Capital Cost Study*, UMTA-MD-08-7001, Urban Mass Transportation Administration, U.S. Department of Transportation, 1991.
Schaevitz, R.C. "Use of Life-Cycle Cost Analysis in Transit Capital Overhaul/Replace Decisions — An Application to the PATH Railcar Fleet," *Transportation Research Record, 1165*, 1988.
The dollar values are inflated to 1992 dollars by using CPI in *Economic Report of the President, Transmitted to the Congress*, U.S. Government Printing Office, Washington, D.C., 1994.

4.3.1.2. Guideway Cost: There are three types of guideways currently used, namely, at-grade guideways, elevated guideways, and subways. The unit costs on a per-mile basis for different types of guideways are different. In addition to the initial capital cost, rehabilitation and replacement of guideways are necessary to maintain them. The cash-flow diagram for guideway cost is illustrated in Figure 4.10.



P_I = Initial Capital Cost; S = Salvage Value; T = Guideway Life;
P_{R1} = 1st Rehabilitation Cost; T_{R1} = 1st Rehabilitation Schedule;
P_{R2} = 2nd Rehabilitation Cost; T_{R2} = 2nd Rehabilitation Schedule;
P_{R3} = 3rd Rehabilitation Cost; T_{R3} = 3rd Rehabilitation Schedule.

Figure 4.10 Cash-flow diagram of rail guideway cost

As shown in the figure, a total of three rehabilitations are scheduled during the life-span of the guideway. The annualized life-cycle cost of a guideway can be expressed mathematically as:

$$A_{R-G} = 5280 \cdot L_G \cdot \Big[P_I \cdot (A/P, r, t_r) \cdot (P/A, i, t_r) \cdot (A/P, i, T) + \sum_{j=1}^{3} P_{Rj} \cdot (P/F, i, T_{Rj}) \cdot (A/P, i, T) - S \cdot (A/F, i, T)\Big] \quad \text{(Eq 4.70)}$$

where

A_{R-G} = the annual cost of rail guideway, in dollars per year,
L_G = length of track, in miles,
P_I = (weighted) initial capital cost of track, in dollars per linear foot,
r = loan rate,
t_r = loan period, in years,
i = discount rate,
T = lifetime of track, in years,
P_{Rj} = the jth rehabilitation cost, in dollars per linear foot,
T_{Rj} = the jth rehabilitation schedule, in years, and
S = salvage value, in dollars per linear foot.

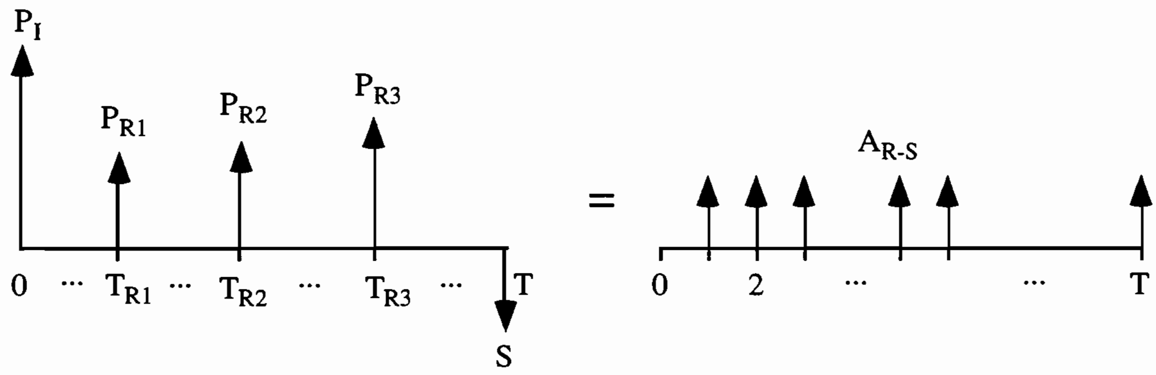
Table 4.15 lists the values derived from previous research.

Table 4.15 Default values for rail guideway cost (1992 dollars)

Item	Symbol	Unit	Default Value
Weighted Avg. Initial Cost	P_I	\$ per foot	1,196
Track Life	T	years	40
Salvage Value	S	\$ per foot	N/A
1st Rehabilitation Cost	P_{R1}	\$ per foot	$0.05P_I$
2nd Rehabilitation Cost	P_{R2}	\$ per foot	$0.10P_I$
3rd Rehabilitation Cost	P_{R3}	\$ per foot	$0.15P_I$
1st Rehabilitation Schedule	T_{O1}	years	10
2nd Rehabilitation Schedule	T_{O2}	years	20
3rd Rehabilitation Schedule	T_{O3}	years	30

Sources: The initial costs of at-grade guideway, elevated guideway, and subway are \$714 per linear feet, \$1,898 per linear feet, and \$7,990 per linear feet, respectively. By assuming that the rail track consists of 85 percent of at-grade guideway, 10 percent elevated guideway, and 5 percent subway, we get \$1,196 per linear foot as the weighted cost of rail track.
Booz-Allen & Hamilton, Inc. *Light Rail Transit Capital Cost Study*, UMTA-MD-08-7001, Urban Mass Transportation Administration, U.S. Department of Transportation, 1991.
Peskin, R. L. "Methodology for Projecting Rail Transit Rehabilitation and Replacement Capital Financing Needs," *Transportation Research Record, 1165*, 1988.
The dollar values are inflated to 1992 dollars by using CPI in *Economic Report of the President, Transmitted to the Congress*, U.S. Government Printing Office, Washington, D.C., 1994.

4.3.1.3. Station Cost: As with the rail guideways, rail stations and terminals are important components of the transit system. Station operations strongly affect passenger convenience, comfort, and safety on the one hand, and service reliability, operating speed, and line capacity on the other. In this study it is assumed that rail stations have three rehabilitation schedules during their lifetime. The cash-flow diagram is shown in Figure 4.11.



P_I = Initial Capital Cost; S = Salvage Value; T = Station Life;
P_{R1} = 1st Rehabilitation Cost; T_{R1} = 1st Rehabilitation Schedule;
P_{R2} = 2nd Rehabilitation Cost; T_{R2} = 2nd Rehabilitation Schedule;
P_{R3} = 3rd Rehabilitation Cost; T_{R3} = 3rd Rehabilitation Schedule.

Figure 4.11 Cash-flow diagram of rail station cost

Mathematically, the annualized life-cycle cost of stations is determined by

$$A_{R-S} = N_S \cdot \Big[P_I \cdot (A/P, r, t_r) \cdot (P/A, i, t_r) \cdot (A/P, i, T) + \sum_{j=1}^{3} P_{Rj} \cdot (P/F, i, T_{Rj}) \cdot (A/P, i, T) - S \cdot (A/F, i, T)\Big] \quad \text{(Eq 4.71)}$$

where

$A_{R\text{-}S}$ = the annual cost of rail stations, in dollars per year,

N_S = number of stations on the corridor(s), or $N_S = L_G / (2 \cdot L_S) + 1$,

P_I = initial capital cost of a station, in dollars per station,

r = loan rate,

t_r = loan period, in years,

i = discount rate,

T = life time of stations, in years,

P_{Rj} = the jth rehabilitation cost, in dollars per station,

T_{Rj} = the jth rehabilitation schedule, in years,

S = salvage value, in dollars per station,

L_G = length of track, in miles, and

L_S = average inter-station spacing, in miles.

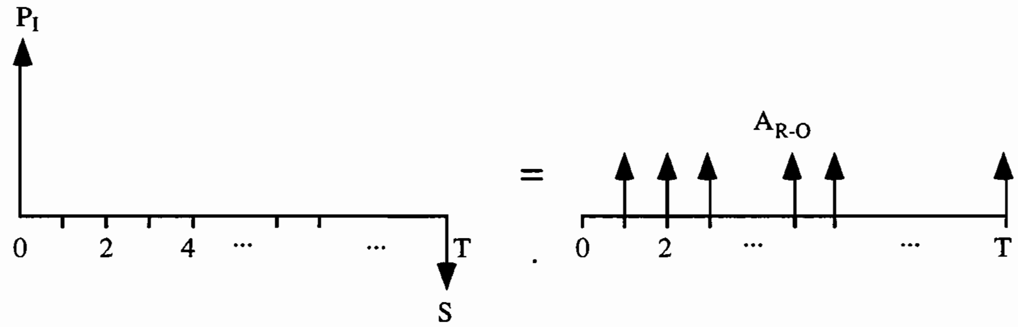
The default values obtained from other researchers are listed in Table 4.16.

Table 4.16 Default values for rail station cost (1992 dollars)

Item	Symbol	Unit	Default Value
Initial Capital Cost	P_I	\$ per station	-
Station Life	T	years	40
Salvage Value	S	\$ per station	N/A
1st Rehabilitation Cost	P_{R1}	\$ per station	$0.014P_I$
2nd Rehabilitation Cost	P_{R2}	\$ per station	$0.108P_I$
3rd Rehabilitation Cost	P_{R3}	\$ per station	$0.052P_I$
1st Rehabilitation Schedule	T_{O1}	years	10
2nd Rehabilitation Schedule	T_{O2}	years	20
3rd Rehabilitation Schedule	T_{O3}	years	30

Source: Booz-Allen & Hamilton, Inc. *Light Rail Transit Capital Cost Study*, UMTA-MD-08-7001, Urban Mass Transportation Administration, U.S. Department of Transportation, 1991.
Peskin, R. L. "Methodology for Projecting Rail Transit Rehabilitation and Replacement Capital Financing Needs," *Transportation Research Record, 1165*, 1988.
The dollar values are inflated to 1992 dollars by using CPI in *Economic Report of the President, Transmitted to the Congress*, U.S. Government Printing Office, Washington, D.C., 1994.

4.3.1.4. Other Facility Costs: The other facility costs include the spending on right-of-way, yards and shops, systems, soft costs, and special conditions. The yards include storage tracks, and shops for regular car maintenance, inspection, and minor repairs. The system costs are attributed to the purchase of signals, power communication, fare collection, etc. The soft costs include the costs of engineering, project management, and research. The special conditions involve utility relocation and roadway changes. It is assumed that there is no major rehabilitation scheduled during the life of these facilities, and that only routine maintenance is required. The cash-flow diagram is shown in Figure 4.12.



P_I = Initial Capital Cost; S = Salvage Value; T = Life.

Figure 4.12 Cash-flow diagram of other facility cost for rail

i) ROW Cost

The costs are formulated as

$$A_{R-ROW} = P_I \cdot (A/P, r, t_r) \cdot (P/A, i, t_r) \cdot (A/P, i, T) - S \cdot (A/F, i, T) \qquad \text{(Eq 4.72)}$$

where

A_{R-ROW} = the annual cost of rail right-of-way, in dollars per year,
P_I = initial capital cost of right-of-way, in dollars,
r = loan rate,
t_r = loan period, in years,
i = discount rate,
T = lifetime of right-of-way, in years, and
S = salvage value, in dollars.

ii) Yards and Shops Cost

Mathematically, the annualized costs are

$$A_{R-YS} = N_{YS} \cdot \left[P_I \cdot (A/P, r, t_r) \cdot (P/A, i, t_r) \cdot (A/P, i, T) - S \cdot (A/F, i, T)\right] \qquad \text{(Eq 4.73)}$$

where

$A_{R\text{--}YS}$ = the annual cost of rail yards and shops, in dollars per year,
N_{YS} = number of yards and shops,
P_I = initial capital cost of yards and shops, in dollars,
r = loan rate,

t_r = loan period, in years,
i = discount rate,
T = lifetime of right-of-way, in years, and
S = salvage value, in dollars.

iii) System Cost, Soft Cost, and Special Condition Cost

There are no salvage values associated with these costs. Mathematically

$$A_{R-SSS} = 5280 \cdot L_G \cdot \left[P_I \cdot (A/P, r, t_r) \cdot (P/A, i, t_r) \cdot (A/P, i, T)\right] \quad \text{(Eq 4.74)}$$

where

$A_{R\text{--}SSS}$ = the annual cost of systems, soft, and special, in dollars per year,
L_G = length of track,
P_I = initial capital cost of system, soft, and special, in dollars per linear foot,
r = loan rate,
t_r = loan period, in years,
i = discount rate,
T = lifetime of track, in years, and
S = salvage value, in dollars.

Table 4.17 lists some of the default values.

Table 4.17 Default values for other facility costs for rail (1992 dollars)

Item	Symbol	Unit	Default Value
ROW	P_I	$	N/A
Yards and Shops	P_I	$ per yard and shop	
Life of Yards and Shops	T	years	40
Salvage Value	S	$ per station	N/A
Systems	P_I	$ per linear foot	
Soft	P_I	$ per linear foot	
Special Conditions	P_I	$ per linear foot	

Source: Booz-Allen & Hamilton, Inc. *Light Rail Transit Capital Cost Study*, UMTA-MD-08-7001, Urban Mass Transportation Administration, U.S. Department of Transportation, 1991.
The dollar values are inflated to 1992 dollars by using CPI in *Economic Report of the President, Transmitted to the Congress*, U.S. Government Printing Office, Washington, D.C., 1994.

4.3.2. Rail External Cost

The external costs borne by rail users include travel time cost, pollution cost, and other costs. No accident cost and incident delay cost are considered in this report.

4.3.2.1. Travel Time Cost

i) In-Vehicle Time

The in-vehicle travel time by train depends directly on inter-station distance, acceleration and deceleration rates of the train, and maximum speed of the train. The impact of maximum speed on travel time increases rapidly as the inter-station distance gets longer. Acceleration and deceleration rates, on the other hand, strongly influence travel time for shorter distances.

Let S_c be the distance required for a train to accelerate to maximum speed; then let the train immediately apply braking and come to a full stop. For all station spacing $S<S_c$ travel consists of acceleration, deceleration, and standing time at stations. For spacing with $S>S_c$, equations vary depending on what travel regimes are applied.[32]

The critical inter-station spacing S_c, as well as travel time between stations, is formulated as[33]

$$S_c = \frac{V_{max}^2}{25.92} \cdot \frac{2}{a} \qquad \text{(Eq 4.75)}$$

and

$$T_{R-in} = \left(\frac{3.6 \cdot 1610 \cdot L_S}{V_{max}} + \frac{V_{max}}{7.2} \cdot \frac{2}{a} + t_s \right) / 3600 \qquad L_S > S_c$$

$$T_{R-in} = \left(\sqrt{\frac{4 \cdot a \cdot 1610 \cdot L_S}{a^2}} + t_s \right) / 3600 \qquad L_S < S_c \qquad \text{(Eq 4.76)}$$

where

T_{R-in} = in-vehicle travel time between two adjacent stations, in hours,

V_{max} = maximum speed of train, in km/h,

a = acceleration/deceleration rate, in m/s^2,

L_S = inter-station spacing, in miles, and

t_s = standing time at a station, in seconds.

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[32] Three regimes existing, namely 1) no coasting; 2) no constant speed; and 3) with constant speed and coasting.

[33] Vuchic, V. R. *Urban Public Transportation — Systems and Technology*, Prentice-Hall, 1981.

ii) Out-of-Vehicle Time

The out-of-vehicle time of a rail user, like that of bus travelers, includes his/her time spent at the station and/or terminal to wait for a train, and time spent in walking from origin to station and from station to destination. The waiting time at the station is defaulted as one-half of the train headway.[34] Thus, the out-of-vehicle time can be expressed as

$$T_{R-out} = T_{o-s} + \frac{1}{2} T_H + T_{s-d} \quad \text{(Eq 4.77)}$$

where

$T_{R\text{-}out}$ = average out-of-vehicle time by a rail user, in hours per trip,

$T_{o\text{-}s}$ = average time from origin to station, in hours per trip,

T_H = average train headway, in hours, and

$T_{s\text{-}d}$ = average time from station to destination, in hours per trip.

iii) Total Travel Time Cost by Rail Users

Overall, the annual total travel time costs by rail travelers can be expressed as

$$A_{R-time} = \omega \cdot \beta \cdot \left(\frac{T_{R-in}}{L_S} + \frac{T_{R-out}}{L_{trip}} \right)_i \cdot N_{car} \cdot VMT_R \quad \text{(Eq 4.78)}$$

where

$A_{R\text{-}time}$ = total travel time cost by rail users, in dollars per year,

ω = the average rail car occupancy, in passengers per car,

β = the travelers' value of time, in dollars per passenger per hour,

$T_{R\text{-}in}$ = average in-vehicle time (between two adjacent stations) by a rail user, in hours,

$T_{R\text{-}out}$ = average out-of-vehicle time by a rail user, in hours per trip,

L_{trip} = average trip length by a rail traveler, in miles per trip,

L_S = average inter-station spacing,

N_{car} = average number of cars a vehicle (train) has, and

VMT_R = the annual rail VMT on the corridor(s).

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34 Larson, R. C., and A. R. Odoni. *Urban Operations Research*, Prentice-Hall Inc., NJ, 1981.

As mentioned in section 4.3.1.1., the number of cars operated by a transit agency depends on the speed of the vehicle, headway, standing time at stations, etc. It is estimated by

$$N_V = \frac{L_G}{L_S} \cdot \frac{T_{R-in}}{H} \cdot N_{car} + N_{backup} \qquad \text{(Eq 4.79)}$$

where

N_V = number of cars operated by transit agency,

L_G = length of track(s), in miles,

L_S = inter-station spacing, in miles,

$T_{R\text{-}in}$ = in-vehicle travel time (see Eq 4.76),

H = peak-hour headway of train, in hours,

N_{car} = average number of cars a vehicle (train) has, and

N_{backup} = number of backup cars the transit agency has.

4.3.2.2. Pollution Cost by Rail Users: Because they are powered by electricity, rail vehicles don't pollute the air as directly as do autos and buses. However, the power plants generating the electric power used to drive rail vehicles cause significant air pollution. Table 4.18 gives the basic emission rates of the different types of electric power plants.

Table 4.18 Emissions of electricity generating plants (g/kwh)

	HC	CO	NO_X	SO_X	PM
Coal	0.058	0.80	2.5	1.0	0.1
Natural Gas	0.006	0.12	1.7	0.0024	0
Nuclear	0	0	0	0	0
Hydra	0	0	0	0	0

The results in g/mile are obtained by dividing the g/kwh at the outlet pollution rate of the plant by the mile/kwh at the outlet efficiency of the rail vehicles. Since emissions from the plant are independent of the drive cycle of the vehicles and are probably relatively constant, the relevant conversion factor is the average lifetime mile/kwh efficiency — E_v — of the vehicles.

The damage values of the pollutants, shown in Table 4.4, depend on the region and on the weather. By using the figures in Table 4.4, we can write the pollution costs by rail systems as

$$A_{R-pl} = \sum_{p=1}^{5}\left(\frac{VMT_R}{E_v}\cdot\gamma_p\cdot\sum_{i=1}^{4}\left(m_{pi}\cdot p_i\right)\right) \qquad \text{(Eq 4.80)}$$

where

p = a pollutant,

γ_p = the damage value for pollutant p, in dollars per gram,

VMT_R = annual VMT by rail vehicles on the corridor(s),

E_v = rail vehicle outlet efficiency, in VMT/kwh,

m_{pi} = emission rate for pollutant p by type i plant (see Table 4.18), and

p_i = percentage of type i plant used for charging and recharging.

4.3.2.3. Other External Costs: There are other external costs associated with rail users. But because the study of these externalities is beyond the scope of this study, we cite only the findings of previous researchers. Details are provided in a previous report.

Table 4.19 Other externalities (in ¢ per rail PMT)

Externality	Brief	Cost
Local Government	Costs not counted for in facility cost.	0.13
Noise	Costs due to noise.	0.16
Building Damage	Damage caused by vibration in buildings.	-
Loss of Aesthetics	Aesthetic damage by transportation.	-
Water Pollution	Water pollution and oil spills.	-
Weather Change	Damage of global warming by CO_2 emission.	-
Wetlands	Wetland loss due to roadway construction.	-
Proper Values	Negative impact on land by traffic artery.	-
Land Loss	Land loss related to automobile.	-
Energy Security	Cost of uncertainty of energy market.	0.39 - 1.3

Source: Miller, P., and J. Moffet. *The Price of Mobility — Uncovering the Hidden Costs of Transportation*, Natural Resources Defense Council, 1993.
Missing data are primarily due to the lack of quantitative studies in those areas.

4.3.2.4. Annualized Total External Costs by Rail Users: As we did in calculating external costs for auto and bus users, we use annualized external cost as our criterion in calculating total cost. This is expressed as

$$A_{R-ex} = \left(\sum_{t=0}^{T}\left(A_{R-ex}^{t}\cdot(P/F, i, t)\right)\right)\cdot(A/P, i, T) \qquad \text{(Eq 4.81)}$$

where

$A_{R\text{-}ex}$ = annualized external cost, in dollars per year,

A^{t}_{R-ex} = total annual external costs (including costs of travel time, air pollution, and others) in year t, in dollars per year,

i = discount rate, and

T = lifetime of the facility, in year.

4.3.3. Operating Cost

Rail transit agency operating costs involve operating and maintenance costs and administration costs. The costs are flexible and depend on facilities operated by the transit agency. The administration cost involves engineering staffs as well as labor costs. We represent these costs as user inputs in MODECOST.

CHAPTER 5. CONCLUSION

How much does it really cost to drive a car, ride a bus, or even ride rail transit? The proposed answers to these questions have led to considerable debate in recent years. There are few studies that integrate all the different aspects of roadway costs into a comprehensive analysis of the total costs of roadway use. As reviewed in the previous report, most full-cost studies concentrate on national averages. Averages, however, are misleading in many cases because dramatic differences from one locale to another lead to large variations in costs. In this study, we developed a working model that takes into account the significant impact of these variations. The model was developed from a system cost perspective to justify resource allocation in the face of increased competition for limited funds — a method that creates a balanced investment strategy that is not biased towards any transportation mode. In addition, it provides cost estimates and comparisons for the major urban transportation modes.

In evaluating the findings reported herein, one must give consideration to certain limitations inherent in the study design:

- The study examined transportation costs, not benefits, and should not be used as the sole basis for a cost-benefit analysis;
- Certain costs identified in the analytical model are unmeasurable or are beyond the scope of this study; thus, totals in the matrix understate total transportation costs.

In conjunction with this study, we developed MODECOST, a computer model capable of performing all necessary calculations. MODECOST is an easy-to-implement, interactive and menu-driven, user-friendly software developed for comparing multimodal investment alternatives. The software package is modular in nature, allowing for further enhancement. The potential for software development in this area is tremendous, and the described framework and models in this report promote this flexibility. The software can be run on any IBM-PC or compatible computer equipped with Microsoft Windows 3.0 or up.

The following identifies areas in which further research could broaden our understanding of the economics of transportation:

- Application of the analysis to some regions: The analytic model developed for this study can be applied to an urban transportation networks or corridor(s). It would be possible to determine which alternative is the least-cost option.
- Estimation of the impact of policy recommendations: Policy changes could affect not only the proportion of travel conducted by different modes at different times, but also the costs of travel under each set of parameters.
- Quantification of remaining costs: Further research is needed to estimate those costs remaining unquantifiable. This could lead to a more complete transportation cost accounting process.