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### **Publication Date**

1975-07-01

A METHODOLOGY FOR SELECTING  
URBAN TRANSPORTATION PROJECTS

by

Randall Johnston Pozdena

July 1975

This material was prepared with the support of National Science Foundation grant no. GI-37181. The results and views are the independent product of university research and are not necessarily concurred in by the National Science Foundation.

Institute of Urban and Regional Development  
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### Acknowledgments

This research enjoyed the assistance of many people. I would like to thank, in particular, the guidance of my thesis committee, Theodore Keeler, Leonard Merewitz and Earl Rolph. I would also like to express appreciation for the stimulation provided by my fellow participants in the Transportation Cost Study and the indirect support of the National Science Foundation, the Institute of Traffic and Transportation Engineering and the Institute of Urban and Regional Development at the University of California at Berkeley.

The San Francisco Bay Area Rapid Transit District offered access to its data and resources thanks to the indulgence and interest of Keith Bernard and Ward Belding. Daniel McFadden provided much thoughtful advice that assisted in the formulation of this research, and his own research was a valuable input to mine.

Ruth Suzuki did an admirable job typing this manuscript from sloppy drafts and many readers provided valuable editorial advice.

But perhaps the greatest debt is owed to the CDC 6400 which was nice enough to allow my quadratic programs to converge.



## Introduction

"The principal function of regional rapid transit is to meet enough of the peak period demands so that the more costly alternative of relying solely on freeways ...can be avoided..."

This quotation from the BART Composite Report of 1962 [1] summarizes the primary focus of modern urban transportation planning. The mounting congestion of urban automobile facilities during peak periods of the day combined with the desire to reduce devotion of urban resources to the automobile and the seeming inability of existing public transportation systems to provide competitive alternative carriage is the content of the so-called Urban Transportation Problem.

In this environment of unsatisfactory performance of existing modes of transportation and the public's apparent desire to avoid further reliance on the automobile, transportation planners and engineers have sought to develop public transportation technologies capable of providing relief to urban commuters. In the San Francisco Bay Area, on which much of this study is focussed, the solution took the form of a high-speed, computerized, commuter railroad: the San Francisco Bay Area Rapid Transit District or BART. One and one-half billion dollars later, it has since been asked (in the San Francisco area and elsewhere): "Is the BART-type technology the best solution to the urban transportation problem?"

We attempt in this study to develop an analytical framework within which the relative economic feasibility of transit

alternatives may be examined. It does not provide precise and absolute measures of the social surplus generated by alternatives (no analysis ever can) but does place the problem in a context which allows identification of the likely ranking and magnitude of the benefits created by various transit investments. It permits, moreover, the likely economic consequences of a new technology to be explored within the confines of a model rather than in the expensive and often ungeneralizable context of demonstration projects. The literature contains several important previous attempts to compare the potential of existing and proposed technologies of passenger transportation. Each, in its own way, has attempted to come to grips with the multi-product nature of the analysis; this is the fundamental theoretical difficulty that pervades multi-modal analysis. Meyer, Kain and Wohl [2] approached this problem by uniformly requiring that transit provide a level and quality of service comparable to the automobile; the costs of providing this service were then calculated for each mode and compared. They recognized the multi-dimensional nature of output, but in imposing similarity in most dimensions, they ignore the possibility of trade-offs among the various attributes and the importance of the relative attractiveness of these attributes to different groups of users. Edward Morlok [3], in a dissertation prepared at Northwestern University, chose to recognize the diverse output properties of various technologies directly; he develops a vector of indicators of the various output attributes of the modes and attempts to relate these technological attributes to the costs of providing the service. He is then able

to compare the costs of supplying service via the various modes in a wide range of physical environments.<sup>1</sup> While Morlok's work was a significant contribution to the field of transportation technology evaluation it has several shortcomings from the point of view of the urban transportation economist: it does not deal adequately with attributes of output involving the users (such as transferring, waiting and walking requirements of the various modes); it does not present a framework which allows determination of equilibrium flows when there are several competing technologies and it does not provide a convenient methodology for assessing the community benefits created by the introduction of a new mode.

It is the intention of this current effort to present a methodology which deals with the multiproduct nature of the urban transportation industry in such a way as to allow convenient analysis of the alternatives without imposing unreasonable restrictions on the characteristics of their output. The methodology acknowledges the different attributes of the outputs of the various modes, but interprets these different attributes as essentially different modal input requirements. Thus the service of the rail transit mode and a conventional bus differ in their relative speeds, but if users are imagined to be co-producers of the output, the speed attribute can be related to the demand for a particular input -- users' in-vehicle time. Most of the output-differentiating attributes of urban transportation technologies can be incorporated in an expanded or "generalized" cost function which values users'

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<sup>1</sup>The descriptors of the physical environment were such things as connectivity and technical density of the transportation network, and capacity requirements. The emphasis of Morlok's work was on intercity rather than urban transportation.

inputs and the feasibility analysis can proceed in a single product framework.

After establishing the theoretical justification of the methodology, it is necessary to develop relationships for each mode between utilization of the particular service and the user and other inputs required; these relationships will depend on the type of technology and service environment involved. These relationships may then be used in networks to simulate the consequences of the introduction of the technology in various travel environments.

For the purposes of this study, four alternative technologies will be analyzed: a BART-like rapid rail technology, conventional urban bus service and two forms of exclusive lane bus service.<sup>1</sup> The emphasis of the network analysis is on the peak period, although examination of the behavior of the analysis under a wide variety of service environmental conditions is performed.

The results of any simulation or model inevitably depend on the strength of certain assumptions. Many a public project has been "justified" on the basis of generous parameter assumptions, whether it be parameters of demand functions, parameters of cost functions or interest rates [4].

The sensitivity of the results to parameter assumptions is reviewed whenever possible in this study and a fortiori reasoning is used as a guide in employing restrictions or simplifications in

---

<sup>1</sup>These two forms differ only in the right-of-way used. In one case (the exclusive right-of-way version) the buses travel on a specially constructed busway. In the other case (the priority lane version) a lane in each direction on the existing freeway is condemned for exclusive bus use. The alternative of expanded freeway capacity will not be approached here; strong public attitudinal and land-use considerations prevail against this alternative in most urban environments.

the model.

Two types of pricing assumptions will be employed, pricing at marginal generalized cost, and pricing at perceived cost, which is as near as possible to extant pricing policies and individual perceptions of non-monetary costs. The theoretical capability of a mode to attract patrons or generate benefits to the user community under a marginal cost pricing regime is often different from that experienced under the real-world pricing constraints.





CHAPTER ONE  
THE THEORY OF GENERALIZED COSTS

Recent work in the estimation of demand for urban passenger transportation has found some success in the treatment of technologies of movement as bundles of abstract characteristics rather than specifically defined modes [5][6][7]. This "abstract mode" theory properly treats a transit trip as a good which only enters into other production functions (work, recreation, shopping, etc.) and is not consumed as a final good under normal traveller pathologies. An individual is presumed to be concerned only with completing movement between two points at minimum net disutility to his total activity and not with the method or technology per se.

While an abstract-characteristic theory of consumption is quite general [8][9], it has found greater use in transportation than elsewhere because the characteristics of various goods (transportation technologies or modes) are more easily defined and quantified here than elsewhere. For commodity movement, models of inventory and spoilage costs allow abstraction of a theory of demand for various modes quite easily [10]. For passenger traffic, it becomes less easy to quantify the factors that are germane to human demands for movement; the comfort of the ride, the view from the vehicle are all elements of a rational demand for various modes. The fundamental demand, however, is no less abstract than in the case of commodity movements; presumably the movement of the individual over some space is the ultimately demanded input to some other production function. The

"characteristics" of a transportation technology relate to the kind and quantity of goods which the patron must provide to complete production of the trip. In particular, a user finds that he must provide his own time in various ways (waiting at a stop, riding in a vehicle, walking to stops, etc.) as well as expending psychic energy in combatting discomforts and inconveniences of transferring between modes.

Many forms of transportation will perform the basic task, but they do so with varying requirements upon the participation of the user. Since the user is both a producer and consumer of the commodity, he will implicitly value the inputs which he finds himself providing in order to ultimately consume the product -- a trip. A simple reference to consumer theory may illuminate this point.

Consider the consumer,  $h$ , who gets utility  $U^h$  from  $k$  different and mutually exclusive categories of trips, presumably because of the activity that can be performed at the end of the trip. If money and (undifferentiated) time are the only relevant attributes of trip-making, the consumer will try to maximize

$$(1) \quad U^h = U^h(x_1^h, x_2^h, \dots, x_k^h; t_1^h, t_2^h, \dots, t_k^h; t_L^h)$$

where the  $x_i^h$  are the number of trips of type  $i$ ,  $t_i^h$  is the amount of time spent assisting the production of  $x_i^h$  and  $t_L^h$  is the amount of time spent in an income-producing activity.

He will maximize (1) subject to the usual budget constraint

$$(2) \quad \sum_k p_i x_i^h = w t_L^h$$

where  $w$  is the wage and  $p_i$  are the money costs of making trips of type  $i$ , and a time constraint

$$(3) \quad \sum_k t_i + t_L = T$$

where  $T$  is the total stock of time available to the consumer for the given period. A third constraint imposed upon him by the requirements of the transportation technology concerning the amount of his time that will be required to co-produce trips

$$(4) \quad x_i^h = \phi_i^h(t_i^h) .$$

Forming a Lagrangian of (1), (2), (3), and (4), the first order conditions of this maximization yields the constraints and the conditions

$$\frac{\partial U^h}{\partial x_i^h} = \lambda_1^h p_i - \lambda_3^h$$

$$\frac{\partial U^h}{\partial t_i^h} = \lambda_2 + \lambda_3^h \frac{\partial \phi_i^h}{\partial t_i^h}$$

$$\frac{\partial U^h}{\partial t_i^h} = \lambda_2 - \lambda_1^h w$$

where

$\lambda_1^h$  = Lagrangian multiplier associated with (2)

= marginal utility of added income

$\lambda_2^h$  = Lagrangian multiplier associated with (3)

= marginal utility of time

$$\lambda_{3i}^h = \text{Lagrangian multipliers associated with (4)}$$

$$= \text{marginal utility of contributing to the production of } x_i$$

$$\frac{\partial \phi_i^h}{\partial t_i^h} = \text{marginal productivity of } t_i^h \text{ in producing } x_i .$$

The demand for a particular trip type will be a function of what might be termed the "perceived cost"

$$\lambda_1^h p_i - \lambda_{3i}^h$$

the utility of the money foregone and the disutility experienced in helping produce  $x_i$ . The valuation the user will implicitly put upon his time spent in travel will then be a function of wage-earning alternative opportunities and the pleasurable or displeasurable nature of helping to produce the trip. Namely, the value of time in use  $i$  equals

$$\frac{\frac{\partial U^h}{\partial t_i^h}}{\lambda^h} = w \left[ \frac{\lambda_2^h + \lambda_{3i}^h \frac{\partial \phi_i^h}{\partial t_i^h}}{\lambda_2^h - \frac{\partial U^h}{\partial t_L^h}} \right]$$

This is likely to be less than the wage,  $w$ , if work is onerous, i.e.

$$\partial U^h / \partial t_L^h < 0$$

and/or if the traveler enjoys participating in the production of trips, i.e. if

$$\lambda_{3i}^h \frac{\partial \phi_i^h}{\partial t_i^h} < 0 \quad .$$

Clearly, different individuals will face different wage-earning opportunities and will have different perceptions of the onerous nature of trip production. Hence, the value of time will differ among individuals.

However, the basic motivation that consumer theory provides is that demand for particular modes of travel is a result of the different ways in which the various technologies require the participation of the user. If the relevant attributes of the trip could be identified and the proper user's implicit valuation of these attributes identified, "generalized cost" functions could be developed. This amodal treatment of transportation demand could significantly facilitate the study of project feasibility, as outlined in CHAPTER TWO.

Modifying slightly the model of consumer behavior presented above, we can show that the use of a generalized cost function requires the valuation of time components of trip-making at the marginal values calculated above, but that the first-order conditions for a Pareto-optimum are very much analogous to those in the usual, multi-product analysis of consumption. This will justify our use of the amodal demand/generalized cost approach to project analysis.

This may be demonstrated in the following fashion. The community seeks to maximize the sum of individual utilities,  $u^i$ ; the individual utility functions have as their argument the number

of trips  $x^i$  per period and the individual's income after transportation costs of  $y^i$ . (For simplicity, there is only one type of trip possible.) Utility is to be maximized subject to first the constraint that the time spent travelling per trip is  $t_i$  and  $t_i$  is a function of the total trips made by the community in the period. That is

$$t^i = T\left(\sum_j x^j\right) \quad \text{for all } i \quad .$$

The second constraint is the budget constraint that total community income,  $R$ , not be exceeded by the sum of trip costs and the  $y_i$ . The trip costs  $C$  are the generalized trip costs discussed above such that

$$C = C(x^i, t^i) = x^i(p^i + V^i t^i)$$

where  $p^i$  is the money cost of each trip and  $V^i$  is the value of time to the user. Then the second constraint may be written

$$R = C + \sum y_i \quad .$$

The Lagrangian,  $L$ , associated with this maximization is then of the form

$$L = \sum_i w^i u^i(x^i, y^i) + \beta(t^i - T(\sum_j x^j)) + \alpha(R - C(x^i, t^i) - \sum_j y_j)$$

where the Lagrange multiplier,  $\alpha$ , may be interpreted as the marginal utility of added income and  $\beta$  is the marginal utility of additional trip time. The  $w^i$  are weights from a social welfare function. The first order conditions are then as in (5), (6) and (7).

$$(5) \quad w^i \frac{\partial u^i}{\partial x^i} - \beta \frac{\partial T}{\partial x^i} - \alpha \frac{\partial C}{\partial x^i} = 0$$

$$(6) \quad w^i \frac{\partial u^i}{\partial t_i} + \beta - \alpha \frac{\partial C}{\partial t_i} = 0$$

$$(7) \quad w^i \frac{\partial u^i}{\partial y^i} - \alpha = 0 \quad .$$

Solving (6) for  $\beta$  and substituting in (5) gives

$$w^i \frac{\partial u^i}{\partial x^i} - \frac{\partial T}{\partial x^i} \left( \alpha \frac{\partial C}{\partial t_i} - w^i \frac{\partial u^i}{\partial t_i} \right) - \alpha \frac{\partial C}{\partial x^i} = 0 \quad .$$

Dividing both sides by  $\alpha$  and rearranging terms yields

$$(8) \quad w^i \frac{\partial u^i}{\partial x^i} / \alpha + w^i \frac{\partial T}{\partial x^i} \cdot \frac{\partial u^i}{\partial t_i} / \alpha = \frac{\partial C}{\partial x^i} + \frac{\partial C}{\partial t_i} \cdot \frac{\partial T}{\partial x^i} \quad .$$

The first term of the left-hand side is the "marginal utility of cups in money terms" (sometimes called "marginal benefit"). The expression  $\frac{\partial u^i}{\partial t_i} / \alpha$  in the second term may be interpreted as the "marginal utility of time in money terms" or more simply "the marginal value of time." We may reduce (8) to the conventional Pareto condition for social surplus calculations that

$$w^i \frac{\partial u^i}{\partial x^i} / \alpha = \frac{\partial C}{\partial x^i}$$

("marginal social benefit equals marginal cost") if we can assume that

$$\frac{\partial C}{\partial t_i} = w^i \frac{\partial u^i}{\partial t_i} / \alpha \quad .$$



That is, the value of time used in constructing the generalized cost function,  $C$ , must equal the marginal value of time to the users weighted by the social weight  $w^i$ .

The estimation of the implicit valuation of the attributes of urban transportation technologies is performed by observing the modal choices of individuals when confronted with alternatives displaying a range of these attributes. The theory of estimating the parameters of individual behavior models from observations of a population is receiving a growing amount of attention in the literature [ 11 ] [ 12 ] [ 13 ], and will not be discussed in much detail here except as a motivation for the use of the parameters estimated in these models in perceived cost functions.

The observation that has motivated the most recent efforts to estimate modal choice models [ 14 ] [ 15 ] is that urban trip-making decisions involve discrete choices and not continuous quantitative choices as the simplified model of consumer behavior above postulated. Looked at in the aggregate, the population behaves as if the decisions were continuous, but the model of individual behavior should reflect the lumpiness of the decision process.

The utility that an individual receives from the use of a particular mode  $i$  is a function of the vector of attributes or characteristics of the mode,  $x^i$ . Thus

$$U^i = U^i(x^i) \quad .$$

If  $U^i$  is linear in the attributes  $x^i$ , say,

$$(9) \quad U^i = a_1 x_1^i + a_2 x_2^i + \dots + a_n x_n^i$$

the tripmakers will select mode  $i$  over mode  $j$  if

$$U^i > U^j ,$$

that is, if

$$(10) \quad a_1(x_1^i - x_1^j) + a_2(x_2^i - x_2^j) + \dots + a_n(x_n^i - x_n^j) > 0 .$$

The parameters of (9) could be estimated from individuals' responses if we could put them in an experimental environment and vary widely the technologies to which the individuals were exposed -- an unlikely alternative. The only available data is on population mode choices, and individuals within the population are likely to differ in their perception of the various attributes of the modes and to have variations in taste and other environmental factors which are not accounted for in a single specification of (9).

Suppose, however, that these unobserved elements enter the utility function in an additive fashion and are distributed by the Weibull distribution. Then the probability of (10) occurring for any randomly drawn member of the population is given by the cumulative logistic function, as in McFadden [13] [17], so that

$$\text{Prob}[\text{of selecting mode } i \text{ over mode } j] = 1/(1+e^{-V})$$

where  $V$  is the left-hand side of (10). The estimation of this logit response curve is the kernel of the recent efforts of transportation demand estimation. Once the parameters of  $V$  have been estimated, implicit valuations of the population of the attributes

catalogued in the vector  $x$  may be calculated. If money costs are one of the attributes in the vector  $x$ , marginal dollar valuation of the other attributes may be simply calculated. If, for example,  $\bar{a}_1$  is the estimated coefficient of money expenditures on transportation and if  $\bar{a}_2$  is the estimated coefficient of, say, in-vehicle time, then the value of in-vehicle time in dollars is simply

$$\frac{\frac{\partial U}{\partial \text{money cost}}}{\frac{\partial U}{\partial \text{in-vehicle time}}} = \frac{\bar{a}_1}{\bar{a}_2} .$$

Recent empirical studies of urban transportation demand have produced valuations of many of the important attributes of urban trip-making.\* See Appendix A for a discussion of the time values selected for use in this study.

Given estimates of the value of the attributes, generalized cost functions may be determined for a particular technology by including the subjective valuation of the attributes displayed by

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\*The first application of the conditional logit methodology outlined above to urban transportation choice behavior was a Charles River Associates study using data collected on trip-making behavior in Pittsburgh, Pennsylvania [ 16 ]. This work produced population estimates of the two important modal attributes, walking time and in-vehicle time. These attributes were valued at \$3.05/hr and \$1.10/hr respectively, for work trips and \$5.46/hr and \$ .95/hr respectively for shopping trips. In a pilot study of the BART Impact Studies in the San Francisco Bay Area [ 17 ] a finer characterization of modal attributes was attempted resulting in an overall value of time of \$2.00/hr for work trips, a value of \$3.33/hr for schedule delay, a value of waiting time of \$2.65/hr and a value of a transfer of \$ .15. [See Appendix A for additional discussion.]

each mode. If the list of attributes is complete enough to explain most of the observed preference for one mode over another,\*\* the unit of output need not be identified with the technology for analytical purposes. The two goods become perfect substitutes for one another in the space of total perceived cost. What were previously labelled differences in output characteristics or service have now been embodied in different trip production functions using patron-supplied resources for some of the inputs. Once the valuation of, for example, commuter in-vehicle time is known, it is possible to devise cost functions which include valuations of this input. The quantity of this input required at various outputs of a particular technology can be calculated from technical information about the response of the mode to additional loads. Since the inputs involved in the various production functions are more broadly defined in the case of the abstractly defined output unit than for the usual service-defined output unit, some quite different conclusions may be drawn about economies of scale in various modes since user resources may be economized in a different fashion than pure producer-supplied inputs [18].

Within the context of project selection, an abstract definition of the units of supply and demand simplifies the measurement of the benefit of projects and enables non-existent technologies to be modelled from a knowledge of the technical response of the system to patron loads.

As an example, say that there are  $i$  alternative modes of

---

\* This is generally not completely possible to do. However, a constant term inserted in the modal split function can be interpreted as a pure modal preference effect and its valuation included in that mode's cost function.

travel between two points for a trip of a particular purpose. From a traditional point of view, social surplus,  $W$ , is represented by the line integral

$$(11) W = \int [(f_1 - h_1) dq_1 + (f_2 - h_2) dq_2 + \dots + (f_n - h_n) dq_n]$$

where

$$f_i = f_i(q_1, \dots, q_n)$$

is the inverse of the joint demand function for mode  $i$  and

$$h_i = h_i(q_1, \dots, q_n)$$

is the marginal cost function for mode  $i$ . The complexity of calculating the integral aside, the practical formulation of (11) requires estimates of the (inverse) joint demand functions. There are substantial econometric difficulties to obtaining these estimates and no insights are provided as to the treatment of the demand for new modes of transportation. Thus, as a planning tool, this formulation has limited value in practical applications.

For the abstract mode approach, a single trip-demand function relates the total trip demand to generalized costs. Each alternative means of completing the trip confronts the potential traveler with a different generalized cost. Let  $B(Q)$  be the inverse of the trip demand function,  $Q$  being the total trips demanded between two points for a particular purpose. Associated with the  $i$  distinct alternative routes or modes is a generalized cost function as a function of flow on that alternative of  $c_i(f_i)$ . The equilibrium flow on the various alternatives presented to the users

will be the solution to the following maximization problem:

$$\max W = \int_0^F B(Q)dQ - \sum \int_0^{f_i} h_i(f_i)df_i$$

subject to

$$\sum_i f_i = F$$

$$f_i \geq 0 \quad \text{for all } i \quad .$$

If the  $h_i$  represent marginal social (perceived) costs,  $W$  will be an estimate of social surplus. The familiar Kuhn-Tucker conditions of this benefit maximization process have the interpretation that all routes with positive flow will, in equilibrium, exhibit identical marginal generalized costs.\*

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\* Practical implementation of these measures requires that the above discussed social weights,  $w_i^1$ , all be assumed equal to one, permitting addition of individual utilities.

CHAPTER TWO  
EVALUATING NETWORK IMPROVEMENTS

Most realistically dimensioned transportation planning problems involve consideration of changes in the supply conditions on a network of routes of various modes and between many origins and destinations. Importantly, the abstract-mode approach reduces the multi-mode network traffic allocation problem to one which is methodologically similar to the single-mode allocation problem, for which a large body of literature exists [19][20][21][22] [ 23 ]. Since the abstract mode approach emphasizes the single commodity nature of transportation demand, these network allocation methodologies may now be simply applied to multi-modal planning problems.

Consider a network consisting of a set of "a" arcs. The arcs may be assembled to form  $p$  complete, directed paths between  $w$  origin and destination pairs. The practical measure of social surplus, assuming all individual utilities are additive, then becomes

$$W = \sum_w \int_0^{F_w} B_w(Q) dQ - \sum_a \int_0^{f_a} h_a(f_a) df_a$$

where  $B_w(Q)$  is the inverse of the trip demand function for origin-destination pair  $w$  and  $h_a(f_a)$  is the marginal generalized cost of travel on arc  $a$  as a function of flow on that arc,  $f_a$ , and where, for conservation

$$\begin{aligned} \sum_p F_p &= F_w \\ f_a &= \sum_p m_{ap} F_p \quad \text{for all arcs } a; \quad m_{ap} = \begin{cases} 1 & \text{if } a \text{ is in } p \\ 0 & \text{otherwise} \end{cases} \\ F_p &\geq 0 \quad \text{for all paths } p \end{aligned}$$

Thus from a social point of view, the optimal pattern of trips (and the resulting loads on the network will be that which maximizes  $W$  subject to the conservation constraints).

If the total number of trips per period is taken to be fixed, say  $F_w = \bar{D}_w$  (i.e., the trip demand functions are inelastic with respect to perceived cost), the social optimization problem reduces to the minimization of social cost,  $C$ , where

$$(1) \quad C = \sum_a \int_0^{f_a} h_a(f_a) df_a$$

subject to the conservation constraints

$$(2) \quad \begin{aligned} \sum_p F_p &= \bar{D}_w \\ f_a &= \sum_p m_{ap} F_p \quad \text{for all } a \\ F_p &\geq 0 \quad \text{for all } p \end{aligned}$$

Estimates made of the change in social cost as a result of transportation improvements with the assumption that demands are fixed will generally understate the benefits of the transportation improvement if in fact demands are elastic. This is because individuals will not change their behavior (i.e., change their residence, form car pools, buy or sell a car, etc.) as a result of the change in the transportation system unless to do so gives them additional net benefits. For the purpose of comparing project alternatives, however, the understatement of benefits is not a critical flaw because a project which has larger cost savings over another in a fixed demand model will generally have larger



undiscovered benefits if the true demand function is somewhat elastic. As a decision criterion, it retains its usefulness and the modelling process is simplified considerably.

Imagine the case where all travellers work in a central workplace and reside at  $i$  different locations. The benefits received from housing at location  $i$  are fixed at  $B_i$ . The costs (generalized costs) of getting to work from  $i$  are  $c_i$ , and the number of worktrips made from location  $i$  to the workplace is  $t_i$ . Workers will select their place of residence as a consequence of maximizing total net benefits

$$(3) \quad \sum_i (B_i - c_i) t_i$$

subject to the constraint that the total number of trips is equal to the number of jobs available at the workplace

$$(4) \quad \sum_i t_i = E$$

and the constraint that the supply of housing at each location will respond to the demand

$$(5) \quad t_i = h_i \quad \text{for all } i$$

Forming the Lagrangian

$$L = \sum_i (B_i - c_i) t_i + \lambda_1 (E - \sum_i t_i) + \sum_i \lambda_{2i} (h_i - t_i)$$

the optimal number of trips from each location  $t_i$ , and the equilibrium rent  $\lambda_{2i}$  and the equilibrium wage  $\lambda_1$  would be

determined from the optimization process, given the perceived costs of travel  $c_i$ .

The effect of a change in  $c_i$  can be analyzed by recognizing that (3), (4) and (5) form a linear programming problem and the sensitivity conditions of the primal and dual form of the problem imply

$$\Delta t_i / \Delta h_i = \Delta \lambda_{2i} / \Delta (B_i - c_i)$$

which implies

$$\Delta t_i / \Delta h_i = -\Delta \lambda_{2i} / \Delta c_i$$

since  $B_i$  are assumed to be fixed. Thus

$$\Delta t_i \cdot \Delta c_i = -\Delta \lambda_{2i} \cdot \Delta h_i$$

and since from (5) the number of occupied units of housing is identical to the number of workers residing in the location  $i$ ,

$$(t_i + \Delta t_i)(c_i + \Delta c_i) - t_i c_i = (h_i + \Delta h_i)(\lambda_{2i} + \Delta \lambda_{2i}) - h_i \lambda_{2i}$$

That is, the change in property values at location  $i$  is equal to the total change in costs of transportation to the workplace from location  $i$ .<sup>\*</sup> If the demand for housing at any location responds elastically to a change in rents (that is, locations elsewhere are equally desirable or preferable)

$$\Delta h_i / \Delta \lambda_{2i} < 0$$

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\* An attempt to discover the capitalization of transportation benefits from a longitudinal econometric analysis is reported in J. Moody and R. Pozdena, "The Effects on Property Values of a Rapid Transit Investment," a paper presented at the 1972 Meetings of the Western Economic Association, Santa Clara, California.

and the total property value (and, hence, the localized benefits) may decline at a given location that enjoys an improvement in transportation. The travellers will gain additional benefits by changing their residence and, hence, their trip length. It is this additional increment of transportation benefit that goes unmeasured if demand is assumed inelastic.

It is well known that in the absence of tolls or other charges, the equilibrium flow of traffic on a real transportation network is unlikely to be that which would be determined by the social optimization process outlined above. At best, the users of a transportation system perceive only the average social cost,  $c_a$ , of travelling on arc  $a$ , and not the marginal social cost,  $h_a$ . The equilibrium conditions which we suspect characterize a user optimization process are that users will load the path alternatives available to them until alternate paths between the same origins and destinations exhibit the same average (generalized) social cost. This can be shown to be the first order conditions of the minimization problem

$$C = \sum_a \int_0^{f_a} c_a(f_a) df_a$$

subject to the conservation conditions set forth in (2). The optimum value of  $C$  does not have the interpretation, of course, of social cost, but it can be calculated from the equilibrium average social costs and the equilibrium flows.

It is interesting to note the manner in which this analysis has been extended to allow for several classes of flow, for this

tends itself to an analysis which includes users with different valuations of user inputs. It is likely that a time component, for example, may be valued differently by different classes of users. We suggested above, for example, that different wage-earning opportunities and different perceptions of the onerous nature of working and trip production could give rise to different perceptions of trip cost.

Using the notation above, we may visualize the demands for travel by various groups. Thus  $D_w^k$  is the demand by group  $k$  for travel between some particular origin and destination and for a particular purpose. Further, we may visualize the individual groups as perceiving the costs of travel differently. The function

$$c_a^k = c_a^k(f_a)$$

represents the perception of cost to group  $k$  of a total flow on arc  $a$  of  $f_a$ .

If these groups of users interact uniformly on the network, the individual groups' cost functions are functions of the total flows contributed by all groups. The general form of the minimization problem then becomes

$$(6) \quad \min \sum_k \sum_a \int_0^{f_a^k} c_a^k(f_a^1 + f_a^2 + \dots + f_a^k) df_a^k$$

subject to the constraints

$$\sum_p F_p^k = \bar{D}_w^k \quad \text{for all } k \text{ groups}$$

$$f_a^k = \sum_p m_{ap} F_p^k \quad \text{for all } k \text{ groups, and all arcs, } a$$

$$F_p^k \geq 0 \quad \text{for all } k \text{ groups, and all } p \text{ paths}$$

The interdependence of the various user groups' cost functions, while a useful addition to the model, may not be achieved without some loss of generality in the forms of the cost functions necessary to guarantee the existence of a solution to the minimization problem. The matrix of second partial derivatives of the objective function in (6), namely

$$\left[ \frac{\partial^2 c_a^k}{\partial c_a^j} \right]$$

must be symmetric to insure integrability from the first order conditions that we believe to describe the user equilibrium. In a fully interactive formulation of cost functions as in (5), the practical implication is that the perceived cost functions of the various groups must be parallel in the plane of total arc flows and total perceived cost. This is an unfortunate and not completely realistic limitation.

Conceptually, the solution of the network allocation problems stated above reduce to quadratic or general non-linear programming problems depending upon the exact form of the functions postulated. Certain classes of problems have easier methods. In particular, the problem stated in (6) may be solved by an

algorithm developed by Dafermos and Sparrow if the cost functions are linear or piecewise-linear functions of flow.\* The notation used above is similar to that used in their work [22][24].

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\*The multi-class user problem will not be pursued in the remainder of this work. A non-linear programming algorithm developed by Grinold and Gonzales [25] was used for solution of the network problems used in this research, although others (e.g. [26]) were also explored.

CHAPTER THREE  
AUTOMOBILE COSTS

Line-Haul Auto Costs

The automobile technology requires the joint production activity of several entities. Generally, government units provide the construction and maintenance of the basic roadway surface and the necessary rights-of-way. They also provide a variety of peripheral services to the automobile in the form of law enforcement and judicial activities, administration of vehicle and driver registration (and in some cases, driver training) and public parking facilities. The user provides not only his own time and effort in maneuvering the automobile, but also provides the vehicle capital, operating and maintenance costs. Other private entities supply the auto user with parking and other necessary components of the trip. Society may also incur costs because of accidental damage to persons and property and because of deleterious external effects of the automobile in the form of air, water and noise pollution and the interference of one vehicle with others on the same roadway.

All of these costs should, of course, be accounted for when the social cost of automobile operation is being calculated and the user of automobile services (or any other transportation service or commodity) should be forced to recognize the total resource burden of their trip-making activity. Generally, the user perceives only a fraction of these costs, so that the private, perceived costs will be considerably less than what we have called the generalized social costs. The difficulty involved in accurate

evaluation of any of these costs is, of course, that data on the relationship between auto use and any of these expenses is very sketchy. The social costs of air pollution caused by automobiles, for example, obviously vary in some way with total auto usage. The health or property impact of an additional vehicle mile is different depending upon the total level of driving activity in the region. It is difficult, in other words, to develop total cost functions related to auto use for many of these cost areas because of the scarcity of relevant data. This chapter relies heavily upon the work of others in this area, and in particular upon the work of members of a transportation cost study group at Berkeley in 1973-74 of which I was a participant.\* However, the data in many respects is still very rough and will probably not be susceptible to significant improvement in the future in the absence of improvements in monitoring of the level of automobile services activity and development of improved data bases.

#### Agency Costs

In the context of the automobile, agency costs will refer to costs borne by the non-user portion of the population, including the government and the public at large. In so far as is possible, the costs will be separated into those that remain fixed over a fairly wide range of output and those which vary with the intensity of automobile services usage. The fixed costs include largely the costs of the road surface and the associated structures and

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\* This group was supported by a grant from the National Science Foundation to explore the costs of various modes of transportation within the Bay Area. See the Bibliography for details of this group.



rights-of-way. There are, in addition, capital expenses and other fixed charges associated with providing maintenance and peripheral services, but these are difficult to estimate from existing data and are likely to be small in any case.

A study in 1960 by Hyman Joseph as part of the Chicago Area Transportation Study (CATS) [ 27 ] reported a relationship between the costs of a lane-mile of standard eight-lane highway and residential density of

$$Y = \$999,000 + \$70,800X$$

where  $Y$  is the total construction cost and  $X$  is the residential density in thousands of persons per mile of residential land.

Meyer, Kain, and Wohl [ 28 ] modify this cost formulation to account for the non-proportional influence of the number of lanes on total cost. A facility designed for the joint use of autos, buses and trucks then becomes

$$(1) \quad Y_K = W_C(\$311,000 + \$70,800X) + \$86,000K$$

where  $Y_K$  is the total construction cost of a facility of  $K$ -lanes and  $W_C$  is an adjustment factor which takes on the different values depending upon the facility's characteristics:

2 lanes	$W_C = .65$
4 lanes	$W_C = .77$
6 lanes	$W_C = .88$
8 lanes	$W_C = 1.00$

To determine current replacement cost for a freeway in the Bay Area,

the 1960 relationships reported by Meyer, Kain and Wohl were inflated by a price index published quarterly by the Federal Highway Administration [ 29 ]. Converting from 1960 to 1973 (current) dollars requires multiplying costs by 1.77. (The average rate of growth from 1967 to 1972 in current dollars was roughly 6.2 percent.) A residential density index for the Bay Area comparable to the one used in Joseph's work was not available in the same form. Also, average population densities in the Bay Area are lower than those that would apply to areas suitable for highway construction because of a relatively high amount of land within a county or city that is unuseable for road construction for topographical reasons. Excluding farm land and assuming the same proportion of residential land to total non-farm land, net residential density becomes

$$X = \text{population} \div \left( \frac{\text{area} \times \% \text{ non-farm}}{8} \right) .$$

Using census data, the net residential densities were calculated for Bay Area counties. These are presented in Table 1 below. These densities were then used to calculate the cost per mile and per lane mile for various facilities constructed in the area as a whole using equation (1). This data is presented in Table 2.

In addition to these fixed costs, there are agency costs associated with the automobile that vary with the intensity of the use of the mode. These costs include the following categories.

Maintenance of the roadway

Police, judicial and other peripheral services to auto users

Table 1

## Net Residential Densities of Bay Area Counties

<u>County</u>	<u>Net Residential Density</u> (thousands of persons per square mile)
Alameda	31
Contra Costa	18
Marin	7
San Francisco	127
San Mateo	14
Santa Clara	45
Average Bay Area	25

Table 2

## Replacement Costs of Bay Area Highways (in 1973 dollars)

<u>Facility</u>	<u>Cost/mi</u>	<u>Cost/Lane-mile</u>
2 lane	\$2,699,000	\$1,349,000
4 lane	3,445,000	861,000
6 lane	4,155,000	692,000
8 lane	4,901,000	612,641

Pollution costs (noise and air pollution)

Accident costs (loss of life, wages, property)

While none of these categories is, in reality, likely to be categorized by constant costs with respect to output of the roadway, competing hypotheses are difficult to support and so the assumption is made here that the average vehicle-mile costs in these categories are valid estimates of the incremental costs of a vehicle mile of auto use in these categories. Table 3 below presents estimates made by the transportation cost study group of the average costs in these categories adjusted to 1973 prices.

Table 3

Variable Agency Auto Costs (in 1973 prices)

Maintenance <sup>1</sup>	\$ .0028
Police and administration <sup>2</sup>	.0027
Air pollution <sup>3</sup>	.0048
Noise pollution <sup>4</sup>	.0011
Accident costs <sup>5</sup>	.0335
Other social overhead <sup>6</sup>	<u>.0002</u>
Total \$ .0469 per vehicle-mile	

Source: Keeler, Cluff and Small, "On the average costs of automobile transportation in the San Francisco Bay Area," April 1974.

Notes: 1 - Calculated by summing over the annual maintenance costs of all road-maintaining jurisdictions and dividing by an estimate of total vehicle-miles. See George S. Cluff, "Maintenance cost of California Roads," Berkeley, April 1974.

2 - Calculated by relating the state total expenditures on police and administration to total jurisdiction disbursements and

using this ratio to calculate Bay Area totals in this category. This total was then averaged over total Bay Area vehicle miles.

3 - Assumes vehicle composition is represented by new 1972 vehicles. Calculated by relating the components of the fuel burned and emitted by the vehicle to morbidity and other damage. Illness and death are valued only at the lost wages and medical bills. For additional details see Keeler and Small, "On the environmental costs of the various transportation modes," Transportation Cost Study, Institute of Urban and Regional Development, UC Berkeley, 1974. Unpublished.

4 - See Keeler and Small, above.

5 - Calculated by averaging total national fatalities, serious and minor injuries over annual national vehicle-miles and varying this damage at lost wages and medical expenses. Includes damage to property and the overhead costs of the insurance industry.

6 - This was calculated by Keeler and Cluff [30] by extrapolating the results of a specific study of automobile social overhead in the city of San Francisco by Douglass B. Lee [ 31 ]. Cluff assumed that the ratio of social overhead expenditures to total road capital held across all counties in California. Using this ratio and data on total road capital developed previously by Keeler and Cluff [30], the resultant estimate of annual social overhead expenses were regressed against annual vehicle-miles in the jurisdiction. No significant fixities of expenditures in this category were discovered. The categories of expenses included in this estimate were expenditures (pro-rated to the automobile) on the judicial system, coroner, fire department, public parking,

public health, city planning, schools, recreation and parks.

### User Costs

The user provides a variety of services to the production process. He provides the services of the vehicle capital and the associated operating and maintenance services; in addition, he provides his own time in the vehicle. He may also be required to pay tolls and taxes on road and bridge use and to pay parking charges at least at one end of the trip.

The costs of operating the vehicle consist of direct expenditures on vehicle maintenance, gasoline and oil, tires and interest and depreciation on the vehicle itself. To a substantial extent the well-informed user is able to trade off expenses in one category for savings in another, and the behavior of these expenses over time as the relative prices of the various items of expense change is open to speculation. The recent dramatic increase in fuel prices, for example, has changed the observed equilibrium rate of substitution between vehicle size and fuel. The consumer has changed his willingness at the margin to trade off the safety and spaciousness of a larger vehicle for the fuel economy of a smaller vehicle. Similarly, there is some possibility of trading off interest and depreciation capital for maintenance expenses. Consumers may choose to buy a certain make or vintage of vehicle because of its particular (perceived) maintenance attributes. Or the user may allow more rapid depreciation of the vehicle (reduce its economic life) by economizing on maintenance and repairs. Thus any estimate of the relative or absolute magnitude of user

expenses in these categories is a point estimate and its cost components or absolute magnitude will vary in some unknown fashion over the period to which the present analysis relates.

Meyer, Kain and Wohl [ 32 ] report operating and maintenance costs for "a reasonably economical or compact vehicle" as shown in the first column of Table 4 . The Federal Highway Administration developed typical operating costs for vehicles in the Baltimore, Maryland area [33]. Keeler and Small have adjusted these costs to reflect differences in maintenance laborers wages between the Baltimore and San Francisco areas [ 34 ]. These figures, adjusted to 1973 prices appear in the second column of Table 4 .

Table 4  
Costs of Operating a Compact Automobile

	<u>Meyer, Kain and Wohl</u> (1962?)	<u>FHA/KCS*</u> (1973)
Maintenance and repairs	1.70¢/veh-mile	2.15¢/veh-mile
Tires and accessories	.15	.42
Gasoline (pre-tax)	.95	2.12
Oil	<u>.10</u>	<u>.12</u>
Total	2.90	4.81
Fuel tax (11¢/gallon)	--	.69

Sources: Column 1 - Meyer, Kain and Wohl, p. 218;  
Column 2 - Keeler and Small's 1972 modification of  
FHA data was adjusted by the author to 1973 dollars  
by use of the San Francisco-Oakland consumer price  
index. In addition, a gasoline price (pre-tax) of  
34¢ per gallon was used. Inherent in the figures  
are assumptions of a 10 year, 100,000 mile average  
vehicle utilization. Small also assumed gasoline  
consumption of 15.97 miles per gallon for a compact  
vehicle.

As has been alluded to above, the decision to purchase the

vehicle is made in the context of a constellation of relative prices: maintenance, fuel, insurance, and the costs of other modes of transportation. Once purchased, it may be argued, the proper perception of vehicle interest and depreciation is that the marginal costs of these categories are small or zero. However, the service life of an automobile is very strongly use-related, and various leasing and rental arrangements that exist allow vehicle capital services to be purchased in very small increments. The assumption will be made here, then, that the average cost of vehicle capital services is the marginal cost of these services. Assuming a (1973) price of a compact vehicle of \$3000, uniform serviceability over a 10 year life and annual use of 10,000 miles, at 6%, the annual capital cost is \$399. On a per mile basis,

$$\frac{\text{annual cost}}{\text{vehicle-mile}} = \frac{399}{10,000} = \$ .040$$

The total incremental user costs of operating a compact automobile are then the 4.81 cents per mile of Table 4 plus 4.0 cents in vehicular interest and depreciation, or roughly 8.81 cents per vehicle mile. To these operating expenses must be added the costs of Table 3 representing incremental agency costs. The sum of the cost of non-user time components are displayed in the first column of the table below. Not all of these costs are perceived by users of the transportation system, however. The second column of Table 5 displays those costs that users are likely to perceive in actual trip making.

In addition to these cash or monetized costs the auto trip



Table 5

## The Incremental Costs of the Automobile

	<u>Real Incremental Costs</u>	<u>Perceived Costs</u>
Capital and Operating Costs	8.81¢/veh-mi	8.81¢/veh-mi
Agency Costs (Table 3)	<u>4.69¢/veh-mi</u>	<u>.69 (road tax)</u>
Total	13.5¢/veh-mi	9.5¢/veh-mi

user costs the user some valuation of the time spent in travel. For the automobile, the time spent is considered to be entirely in-vehicle time. The in-vehicle time required to complete a line-haul trip is strongly dependent upon the number of other vehicles sharing the roadway. As vehicle flows increase, the average speed of the vehicles declines. The relationship between speed and flow is one that has been studied extensively in transportation engineering literature and the relationship between flow and speed for a particular facility depends upon a wide range of attributes of the facility. The Highway Capacity Manual [ 35 ] discusses at length the factors that influence the capacity and hence the speed-flow relationships for particular facilities. These factors include lane width, shoulder width, grades, vehicular composition of the traffic, exchanges, etc. For the purpose of this study, a general relationship between speed and flow is needed and there does not appear to be the need or possibility for more precise definition of this relationship. Table 6 reports some results of major studies of the speed-flow relationship. The general form of these functions is

Table 6  
Estimates\* of Speed-Flow Relationships

City	Facility	Estimated Function	R <sup>2</sup>
Chicago <sup>1</sup>	Eisenhower, Edens, & Calumet Expressways	$V = 55.36 - .0129F$	.88
Detroit <sup>2</sup>	Ford Expressway	$V = 54.5 - .0215F$	---
New York <sup>3</sup>	Holland Tunnel	$V = 65.9 - .031F$	---

Sources: 1, 2 - Highway Capacity Manual, p.61.

3 - J.M. Thompson, "A mathematical analysis of traffic flow," Port of New York Authority, 1958.

$$V = \alpha + \beta F$$

where  $V$  is the speed in miles per hour and  $F$  is the flow in vehicles per hour per lane. The time,  $T$ , required for a vehicle to traverse a one-mile section of road as a function of flow is then

$$T = \frac{1}{V} = \frac{1}{\alpha + \beta F}$$

Table 7 charts this time/flow relationship for some values of  $F$  using the parameters of the Ford Expressway.

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\* These relationships were generally estimated for a range of observed speeds between 25 or 30 mph and the free flow speed. At slower speeds, shock-waves and car-following effects interrupt steady flow and these estimates are useful only as rough approximations. There is some data on speed-flow relationships at low speeds which indicates that this approximation is not an unreasonable one. A British study cited in Walters [ 36 ] yielded a relationship of the form  $V = 22.8 - .041F$ .

Table 7  
Time/Flow

<u>F, Flow in vehicles per lane hour</u>	<u>T, Average time required per mile</u>
0	.018
250	.020
500	.022
1000	.030
1500	.045
2000	.087
2300	.200
2500	1.333

Source: Calculated using  $T = \frac{1}{V} = \frac{1}{59.5 - .0215F}$

It can be seen from Table 7 that the relationship between travel time and flow is essentially an exponential one. The functional form of the speed-flow relationships noted above has the disadvantage that for very high flows, the speed implied may be negative; this has drawbacks from a modelling point of view. An alternative, continuous formulation of the travel time/flow relationship widely used in transportation engineering literature is of the form:

$$t = t_0 + K(V/C)^m$$

where  $t$  is total travel time per mile,  $t_0$  is the free flow travel time,  $V$  is the volume of vehicles per lane per hour,  $C$  is the capacity of the lane and  $K$  and  $m$  are constants. The ratio of  $V$  and  $C$  is called the "volume-to-capacity ratio" in the literature, and with observations of the relationship between this ratio and vehicle delay, the values of  $K$  and  $m$  may be estimated. One estimate [37][38] yields the following function

relating travel time and flow:

$$t = .018 + .007(V/C)^3 .$$

The implied speed at "capacity volumes" (when  $V = C$ ) is 40 miles per hour.

In order to establish the relationship between volumes and travel times, the capacity of Bay Area roads must be defined. "Capacity" is an elusive concept and is defined in highway engineering literature in various ways. The Highway Capacity Manual defines capacity under ideal conditions for average multilane facilities to be that which allows a flow of 2,000 passenger cars per hour at 30 to 40 miles per hour. As mentioned above, the Haikalis and Joseph study implicitly yields a capacity measure which is defined at a speed of 40 miles per hour. Adjusting the 2,000 vehicles per lane-hour ideal figure to account for the roughly 5% truck traffic in the Bay Area and adjusting for facility size, yields a real capacity of roughly 1600 car-equivalents per lane hour.

A generalized cost function for line-haul automobile travel consists of the sum of the three categories of costs we have been discussing: agency costs, user operating costs, and user time costs.

Since we will ultimately be concerned with patron flows rather than vehicle flows, it is necessary to specify an average load factor per vehicle. The load factor of an automobile, like any other form of transportation, is a function of the service characteristics and price of the particular mode of transportation. The observed load factor is an equilibrium one dependent upon a set of relative prices; in the commute mode, for example, the load factor is partially a function of the relative price of operating the vehicle

and the transactions costs of seeking carpool riders. For the purposes of this study, the load factor will be assumed to be constant and equal to 1.4 persons per vehicle as estimated by the Division of Bay Toll Crossings [ 39 ]. The total cost, TC, of providing Q patron-trips of average length L miles on a line-haul automobile facility of length M miles can then be written

$$\begin{aligned} TC(Q) = & \text{total capital costs of the roadway} \\ & + \text{agency-borne operating and maintenance costs} \\ & + \text{user-borne operating and maintenance costs} \\ & + \text{user valuation of in-vehicle time} \end{aligned}$$

Algebraically,

$$TC(Q) = K \cdot M + O_A \cdot \frac{Q}{\ell} \cdot L + O_n \cdot \frac{Q}{\ell} \cdot L + Q v_v L [t_o + k \left( \frac{Q}{\ell s C} \right)^m]$$

where TC(Q) = total cost per period of Q trip

K = the appropriate periodic capital charge for the roadway

$O_A$  = average agency operating costs per vehicle mile\*

$O_n$  = average user operating costs per vehicle mile\*

$v_v$  = value of in-vehicle time

s = number of lanes in one direction on the facility

$t_o, k, m$  = parameters of the speed flow relationship

Q = one-way flow in patrons per hour

$\ell$  = average load factor of vehicles

C = capacity of the facility in vehicles per lane/hour

The average cost per trip is then

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\*As discussed above, these costs are assumed to be independent of Q.

$$(2) \quad \frac{TC(Q)}{Q} = \frac{K \cdot M}{Q} + O_A \cdot L + O_n \cdot L + v_v L \left[ t_o + \frac{kQ^m}{(\ell sC)^m} \right] .$$

The incremental cost of a trip is

$$(3) \quad \frac{TC(Q)}{Q} = O_A \cdot L + O_n \cdot L + (m+1) \frac{kQ^m}{(\ell sC)^m} \cdot v_v L + v_v L t_o .$$

A marginal cost pricing regime is not, generally, practicable in the real world context. The user of a roadway generally only perceives average (and not marginal) user time costs plus the operating and maintenance costs of his vehicle. The only roadway costs perceived by the auto user are those embodied in the user tax placed upon gasoline sale or special highway and bridge tolls. The user perception of costs is then

$$(4) \quad O_n \cdot L + v_v L \left[ t_o + \frac{kQ^m}{(\ell sC)^m} \right] + L \cdot y + \text{tolls (if any)}$$

where  $y$  is the user tax per mile. Figure 1 displays the relationship between patronage and marginal social cost (equation (3)) and average perceived cost for a trip and cost environment as described in Table 8.

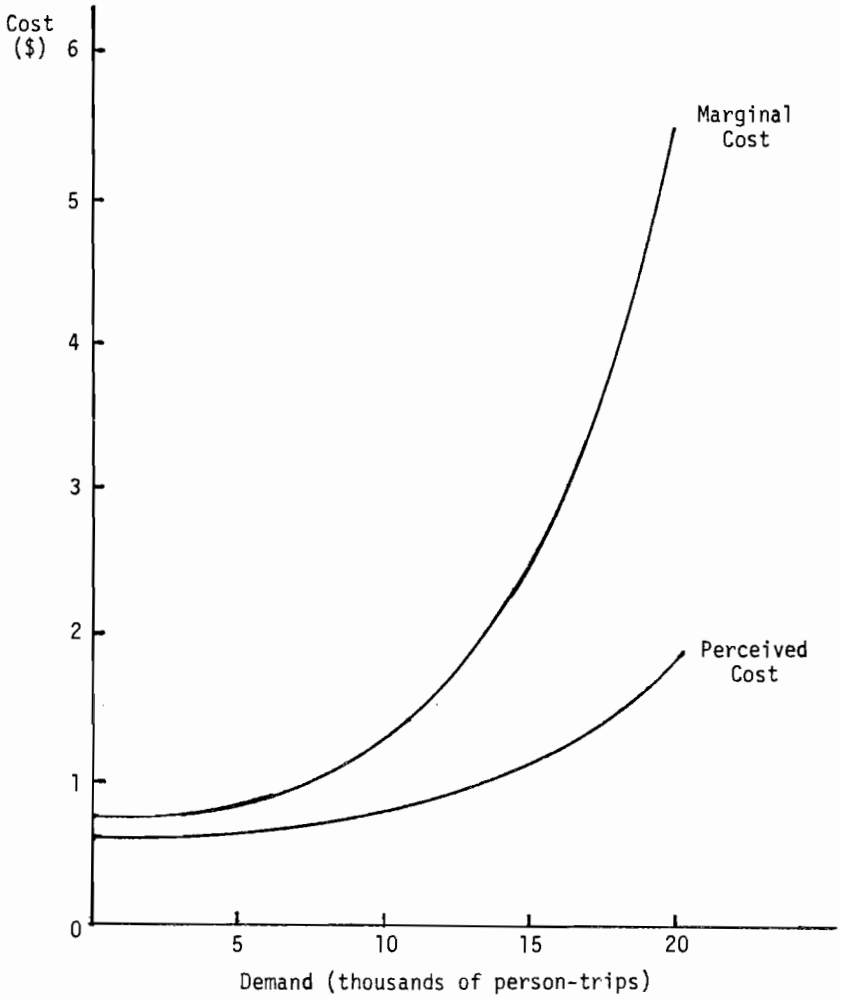


Figure 1: Auto Line-Haul Costs

Table 8

Parameter Values Used in Figure 1

$$O_A = \$ .047 \quad (\text{from Table 3})$$

$$O_U = \$ .088 \quad (\text{from Table 5})$$

$$v_V = 3.0$$

$$s = 4$$

$$k = .007$$

$$m = 3$$

$$t_o = .018$$

$$L = 4.0$$

$$C = 1600$$

$$l = 1.4$$

$$y = .015$$

The equations (3) and (4) describe the basic cost relationship used in the models of the subsequent chapters. With the addition of the access and egress costs developed in Chapter 6, these relationships will be assumed to fully describe the short run costs of automobile use.



## CHAPTER FOUR

## BUS COSTS

This chapter discusses the development of generalized cost functions for the bus mode of urban transportation. These cost functions merge agency costs and user costs and relate these costs to the patron utilization of the system, allowing development of a measure of marginal social cost as well as perceived costs. The discussion focusses on the development of generalized cost functions for integrated conventional bus service and integrated busway service, the two types of service that are the primary interest of this study. The concepts developed, however, could be modified to analyze other types of service.

Agency Costs

The production of seat-mile carriage by bus appears to be characterized by a reproducible technology. That is, uniqueness of the service unit and roadway costs aside, additional seat-miles may be produced at essentially constant average cost per unit to the servicing agency. There have been a number of studies of the urban bus industry which have attempted to establish empirically the constancy of returns-to-scale implied by this reproducibility [ 40 ] [ 41 ] [ 42 ].

The most careful work in this general area of bus costs appears to have been done by Nelson [ 41 ] who uses operating cost data from the American Transit Association for the years 1960 and 1968. The value of capital services involved in the

vehicles themselves cannot be reliably drawn from firm-supplied data because of inconsistencies among accounting methodologies. Nelson instead uses data on the average age of the fleet, the interest rate and a 10% declining balance form of vehicular depreciation in order to develop an estimate of the value bus capital services.\* The cost-function estimated on the two groups of cross section data was of the form:

$$\ln C = a_0 + a_1 \ln B + a_2 \ln w + a_3 \ln VEL \\ + a_4 A + A_5 S + a_6 PUB + a_7 SUB$$

where C = total costs  
 B = bus-miles  
 w = hourly wage  
 VEL = bus-miles/bus-hours  
 A = average age of fleet  
 S = average seats/bus  
 PUB = 1 for publicly-owned; 0 otherwise  
 SUB = proportion of fleet purchased with 1/3:2/3 capital grants

This function may be interpreted as a version of the reduced-form

---

\*The formula used by Nelson to develop the value of capital services was

$$C = P_B e^{-\delta A} (\delta + r)$$

where C = costs of a bus' services to the firm  
 $P_B$  = price of a new bus  
 A = the bus' age  
 $\delta$  = rate of depreciation (assumed by Nelson to be 10% of the value annually)  
 r = the firm's perceived rate of interest

He noted that  $P_B$ , the price of a new bus to the firm, had been significantly affected by federal capital grant policies and under current Urban Mass Transportation Administration regulations, a qualifying agency might perceive a price equal to  $P_B/3$ .

cost function developed from the minimization of total costs subject to a Cobb-Douglas production function of the form

$$(1) \quad Q = \gamma K_B^{\alpha_1} L^{\alpha_2}$$

where  $K_B$  = buses in service per period

$L$  = units of labor in service per period

$Q$  = output in bus-miles per period

$\gamma$  = an efficiency parameter which depends on the service environment of the firm, such as its practicable operating speed.

Minimizing total costs

$$c = P_B K_B + P_L L$$

where  $P_B$  = price of bus services

$P_L$  = price of labor services

subject to (1) yields a cost function of the form

$$c = \gamma \left[ \frac{\alpha_1 + \alpha_2}{\alpha_2} \right] \left( \frac{\alpha_2}{\alpha_1} \right)^{\alpha_1} \frac{1}{\alpha_1 + \alpha_2} P_B^{\frac{\alpha_1}{\alpha_1 + \alpha_2}} \frac{\alpha_2}{\alpha_1 + \alpha_2} P_L^{\frac{\alpha_2}{\alpha_1 + \alpha_2}} \frac{1}{\alpha_1 + \alpha_2} Q$$

which is linear in the logarithm of the terms. Thus the inclusion of VEL in Nelson's formulation may be interpreted as a recognition of bus speed's influence on the constant term  $\gamma$ , while the inclusion of PUB, SUB and A are proxies for differences in the firm's perceptions of the price of bus services.

The author has performed a similar estimation of the reduced form cost function on more recent (1972) data with the following modifications to Nelson's formulation:

1. The value of bus services included in total costs were calculated by using individual vehicle age data, rather than Nelson's use of average fleet age which would tend, given the capital services formula in the footnote on page 40 to understate true bus capital costs. A depreciation rate of 20% on a declining balance was used rather than Nelson's 10% because of its more realistic implications about bus life.

2. The interest rate applicable to each firm was used rather than Nelson's use of public and private firm averages.

3. The perceived replacement cost of bus services was used instead of the three variables SUB, A and PUB as proxies. The perceived replacement cost was calculated as

$$P_B = (\$43,000)(.20 + \text{firm's interest rate})$$

if the firm was private. One-third of this figure was used for public firms (reflecting the availability of federal support for capital grants).

The functional form of the cost function estimated on 42 cross-sectional observations was

$$\ln c = a_0 + a_1 \ln Q + a_2 \ln w + a_3 \ln VEL + a_8 \ln P_B .$$

The results of this estimation are displayed in Table 9 below with Nelson's result from 1960 and 1968:

Table 9

Variable	<u>Pozdena</u>		<u>Nelson</u>			
	1972		1968	1960		
constant	-.562	(.613)	.930	(.557)	.854	(.417)
ln (bus-miles)	1.03	(.0287)	1.013	(.0223)	.982	(.0327)
ln (wage)	1.14	(.196)	.883	(.181)	.785	(.120)
ln (speed)	-.853	(.170)	-.779	(.173)	-.862	(.161)
A			-.00084	(.0055)	-.00375	(.00538)
S			.0010	(.0053)	.00197	(.00197)
SUM			-.059	(.153)		
PUB			-.106	(.0466)	-.0954	(.04444)
ln P <sub>B</sub>	.0684	(.0414)				
R <sup>2</sup>	.990		.990		.994	
# of observations	42		40		45	

Using the results from the 1972 estimation and taking the antilog yields a total cost function of

$$TC(Q) = .570Q^{1.03}W^{1.14}P_B^{.0684}VEL^{-.853}$$

As in the case of Nelson's work, the returns to scale parameter (1/1.03) is insignificantly different from one at the 5% level. That is, as bus-miles (scale) increases by 100% costs increase by 100%. The coefficient associated with the wage implies that a 100% increase in the wage will raise total cost by 114%, a curious result since labor generally represents only about 60% of total bus company costs [43]. This appears to be a demographic effect, however, of higher wages being associated with unionization of transit labor and consequently even higher fringe

benefits and shorter effective work-hours. The coefficient on the price of bus capital services indicates that the increase in bus prices of 100% will increase total costs by roughly 7%. This is within the expected range. The average agency cost per vehicle mile is thus

$$(2) \quad \frac{TC(Q)}{Q} = .570Q^{-.03}w^{1.14}P_B^{.0684}VEL^{-.853}$$

$$AC \approx w^{1.14}P_B^{.0684}VEL^{-.853}$$

Marginal agency costs may also be approximated by this function since the function is characterized by roughly constant costs.

Two major types of bus service will be analyzed in this study: conventional bus service and exclusive lane busway service. These types of service exhibit considerably different service characteristics in an integrated mode of operation. A bus on local streets is assumed to have an average service speed of 12 miles per hour. An arterial bus is assumed to have an average speed of 20 miles per hour. A bus on an exclusive way has an assumed speed of 50 miles per hour.

In general, the overall service speed,  $V$ , will be taken to be a weighted average of the service speeds of the line haul (E) and non-line haul (A) portions of the trip. That is,

$$V = \frac{EV_E + AV_A}{A + E}$$

where  $E$  is the length of the line-haul portion of the integrated trip in miles and  $A$  is the length of the non-line haul trip

components.  $V_E$  and  $V_A$  are the service speeds on each of these components respectively.

The agency costs of providing these services can be calculated from the econometric relationship developed earlier since it is parameterized for service speed,  $VEL$ . The relative dimension, for example, of agency costs for a busway-type service with an overall average service speed of 45 miles per hour and a conventional service with an average speed of 15 miles per hour would be

$$\frac{\text{conventional bus}}{\text{busway bus}} = \frac{w^{1.14} p_B^{.0684} 15^{-.853}}{w^{1.14} p_B^{.0684} 45^{-.853}} = \frac{15^{-.853}}{45^{-.853}} = \left(\frac{1}{3}\right)^{-.853} \approx 2.5$$

so although the conventional bus is three times as slow in this example, it is only 2.5 times as expensive as an exclusive lane bus.

#### Roadway Costs in the Bus Mode

This study is concerned basically with two pricing methodologies, both of them short-run: social marginal cost pricing and a second consisting of existing fare plus perceived user costs. Neither of these methodologies requires that allocations of capital costs be made to the various modes or among different periods of the day. Rather, the net benefits (changes in social cost) of a transportation improvement will be weighted against aggregate capital costs and the allocability of capital costs among different modes or time periods is not of crucial relevance. That is, we imagine society constructing facilities with the potential of producing joint products (peak and off-peak capacity jointly, for example, or auto

or bus roadway joint capacity) and the social surplus (or loss) that accrues to society is weighted against the cost of assembling the joint facility from society's scarce resources. This basic cost/benefit procedure does not require the allocation of these facility costs among uses, but only the aggregate facility costs (which will be compared to aggregate benefits (or cost savings)) to all consumers of the joint products. Most practical methodologies for allocation of capital costs among joint users (and the consequent exercises in average cost pricing) are ad hoc in that they rely a priori on assumptions about the variability of plant capacity or on assumptions about the relative size of benefits to users of each of the joint products. The latter is not known until the pricing experiment has generated equilibrium consumption levels for each of the products and the former ignores the essential fixed-proportions nature of transportation facilities. A bus needs the minimum amount of road capacity whether it is supplying peak or off-peak services. Admittedly additional distinct units of capacity may be required for the peak, but the problem of allocating the minimum capacity remains.

The average cost relationships presented in this and in the following chapters assumes simple averaging of yearly capital service charges over total annual output. The average cost relationships reported are not used for pricing of transportation services, but are presented for a rough representation of the average relationship between incremental and total costs.



### Exclusive Busway

There has been little recent experience on which to base busway rights-of-way acquisition and construction costs. The costs might be expected to be similar to high-quality freeway construction costs, but because of the necessity of grade separation from existing transportation structures and the construction of access ramps and modifications to existing local streets, roads and freeways, the cost of urban busways appears to be much higher than equivalent automobile freeway lane mileage. A study by Wilbur Smith & Associates [44] displayed construction cost estimates for busway surfaces ranging from \$390,000 per lane-mile when built at grade on already graded surfaces to nearly \$2,500,000 per lane-mile when new grade-separated facilities were required. For the purposes of this study, the cost estimates reported by Pittsburgh's Port Authority Transit for their "PAT-ways" of roughly \$2 million per mile [45] are used because of some rough similarities in topographical constraints and urban density between the San Francisco Bay Area and the Pittsburgh area.

### Generalized Costs for a Simple Bus Service Structure

For a simple route of one-way length  $M$  miles and an average service speed of  $V$ , the headway,  $H$ , is

$$H = \frac{2M}{V}$$

and the frequency of the service,  $f$ , is

$$f = \frac{1}{H} = \frac{V}{2M} .$$

The total agency cost of service on this route is thus

$$c = \alpha f = \alpha \frac{V}{2M}$$

where  $\alpha$  is the cost to the agency per route completion. However this cost depends on service speed and the vehicle-mile costs of the service so that

$$\begin{aligned} \alpha &= \text{cost/veh-mile} \cdot \frac{2M}{V} \\ &= (\text{cost/veh-mile}) \cdot V \cdot \frac{2M}{V} \\ &= 2M \cdot A_c \end{aligned}$$

where  $A_c$  = agency cost/vehicle mile of bus service, so that

$$c = M \cdot A_c \cdot f$$

That is, the costs per hour of agency provision of the service,  $c$ , are dependent upon frequency, route length and vehicle-mile costs.

Total in-vehicle time depends upon the average time length,  $L$ , and the average service speed,  $V$ . The time spent in the vehicle by the average user is then

$$t = \frac{L}{V}$$

and the user's perception of the value of this time per user  $v_v t$  where  $v_v$  is the value of in-vehicle time in \$/hour.

The amount of waiting involved in a bus trip depends, of course, on the headways between buses  $H$ . If it is assumed that

the average wait is equal to  $H/2$ , the perceived cost to each user of the time involved in waiting is  $v_H H/2$ .

Ignoring for the moment the costs of the feeder and distribution portions of the trip, the total social cost  $C$  of providing bus service for  $Q$  users on the route described is thus

$$\begin{aligned} C &= M \cdot A_C \cdot f + Q \cdot \frac{Lv_V}{V} + Q \cdot v_H H/2 \\ &= f \cdot M \cdot A_C + Q \cdot \frac{Lv_V}{V} + \frac{Q \cdot v_H}{2f} \end{aligned}$$

The only variable presumed to be in the bus company's control is  $f$ , the frequency of the service. The optimum frequency of service,  $\bar{f}$ , is that which minimizes  $C$ . This minimization yields an optimum frequency of service  $\bar{f}$ ,

$$\bar{f} = \sqrt{v_H Q / 2M \cdot A_C} .$$

Thus optimum service frequency is proportional to the square root of trip demand. This relationship has received the name "the square-root rule" in transportation engineering literature and has been derived in one form or another by several other authors [46] [47] [48].

The minimum social cost of providing  $Q$  bus trips per hour is then

$$\begin{aligned} \bar{c} &= M \cdot A_C \cdot \sqrt{v_H Q / (2M \cdot A_C)} + \frac{Q \cdot v_H}{2\sqrt{v_H Q / (2M \cdot A_C)}} + \frac{Q \cdot Lv_V}{V} \\ &= \sqrt{\frac{v_H Q M \cdot A_C}{2}} + \frac{Q \cdot Lv_V}{V} \end{aligned}$$

The average social cost per user is

$$(3) \quad \bar{c} = \sqrt{\frac{v_H M A_C}{2Q}} + \frac{L v_V}{V}$$

The marginal social cost per user is

$$\frac{\bar{c}}{Q} = \sqrt{\frac{v_H M A_C}{8Q}} + \frac{L v_V}{V}$$

Note that average and marginal costs asymptotically approach  $\frac{L v_V}{V}$  as demand on the system ( $Q$ ) increases. Figure 2 is a graph of average and marginal social costs assuming the following parameter values:

$L$  = average trip length = 5 miles

$M$  = route length = 10 miles

$W$  = average access cost = 0

$A_C$  = bus agency costs = \$1.01/vehicle-mile

$V$  = average bus service speed = 12 mph

$v_V$  = value of in-vehicle time = \$3.00/hour

$v_H$  = value of waiting time = \$7.50/hour

$v_W$  = value of walking time = \$7.50/hour

### Perceived Costs

The analysis above assumes that the price charged by the agency (and perceived by the user) is related to true agency costs and hence, route length and frequency. However, many extant bus pricing schemes are flat-fare schemes and a practical project alternative is one which relies on such a scheme of pricing. Then the average

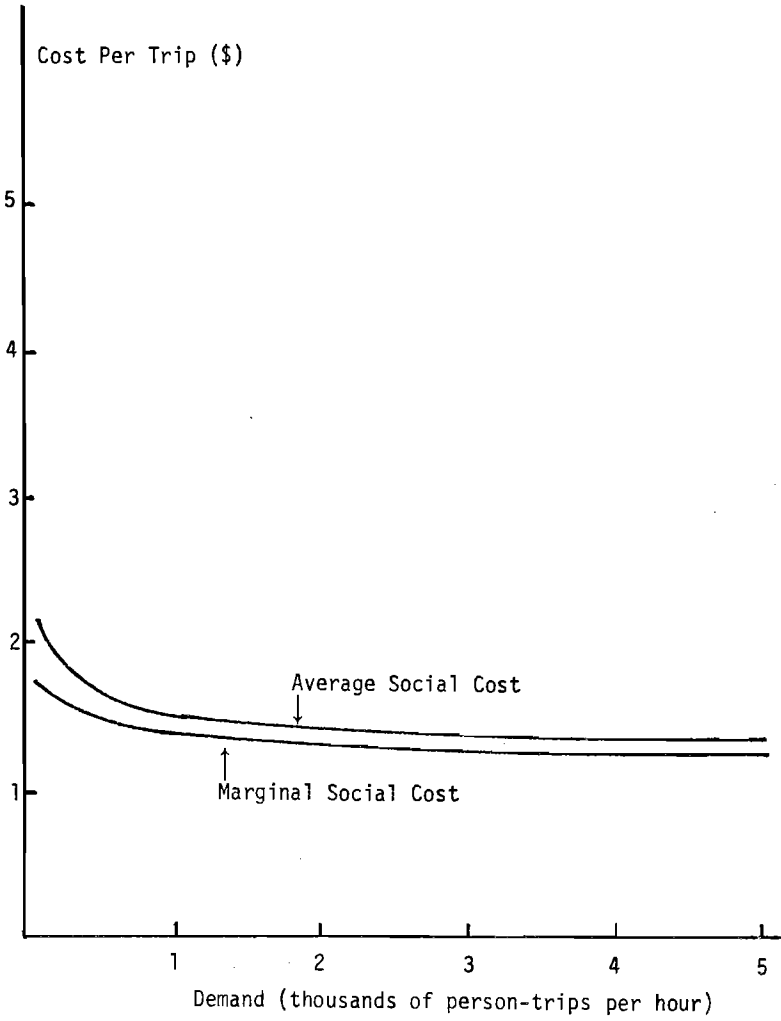


Figure 2: Line-Haul Bus Costs

perceived social cost of equation (11) becomes the average perceived user cost

$$\text{Fare} + \frac{v_H}{2f} + \frac{Lv_V}{V}$$

or

$$\text{Fare} + \frac{2v_H^{MA}c}{Q} + \frac{Lv_V}{V}$$

assuming the dispatch of buses is still the social optimum.

### Generalized Costs for an Integrated Bus Trip

The foregoing discussion derived optimum bus frequencies from the observation that user costs varied inversely with frequency and agency costs varied in direct proportion to this measure of service. However, a bus agency may also select to increase or decrease the number of routes in response to changing demands for service. We must, therefore, establish the trade-off inherent in the bus technology between service frequency and route density. This is particularly important in terms of modelling the integrated (feeder and line-haul service provided by the same vehicle) services that dominate the commute bus mode and which are the hallmark of busway-type service. Here, advocates claim, lie the real advantages of busways over fixed rail transit: not only are line-haul speeds nearly as fast as with rapid rail, but also, access to the high-speed line-haul can be achieved without having to transfer among modes with the concomitant possibility of schedule mismatches and the inconveniences of changing vehicles. The feeder (off busway) portions of the busway lines can have quite diffuse origins,

although they would share the busway facility during line-haul.

The following model was used to develop the generalized cost relationships for this particular type of surface. Feeder lines feed radially in the busway entrances (or in the case of conventional bus service) onto an arterial roadway or freeway. The distance  $d$  is the circumferential distance that the average user of the line has to travel in order to get to the feeder portion of the route. This distance is equivalent to  $\frac{\pi r}{R}$  where  $r$  is the radial distance of the average user from the line-haul terminus and  $R$  is the number of (equally spaced) radial routes. Assuming that the cost per unit distance of access distance  $d$  is  $c$  (see Chapter 6), the total cost to users of access is

$$\frac{c\pi rQ}{R} ,$$

where  $Q$  is again the patron demand for service from the shed area.

Total (generalized) costs are assumed to consist of agency costs, user in-vehicle time costs, user waiting costs, and these costs of user access to the feeder portion of the integrated trip. The agency costs, in a manner similar to the previous discussion, are a function of the number (frequency,  $f$ ) of vehicles serving the entire (feeder plus line-haul) portion of the route. Using the previous notation,

$$\text{Agency costs} = f \cdot M \cdot A_C .$$

The (user) waiting costs are, as before, a function of the frequency of service, but since there are  $R$  routes, the average frequency

along any one route is

$$\frac{f}{R} .$$

Waiting costs, again using previous notation, become

$$\frac{v_H \cdot Q}{2\left(\frac{f}{R}\right)} = \frac{v_H R Q}{2f} .$$

The value of the user's time while in the vehicle is, as before,

$$\frac{v_V L Q}{V} ,$$

where  $V$  is the average service speed over the entire route.

The total generalized costs are then the sum of these agency, waiting, walking, and in-vehicle costs:

$$(4) \text{ Total costs} = TC \\ = f \cdot M \cdot A_C + \frac{v_H \cdot R \cdot Q}{2f} + \frac{c \pi r Q}{R} + \frac{v_V L Q}{V}$$

To find the optimum relationship between bus frequency, route density and demand for trips, the derivatives of equation (4) with respect to each of these variables,  $f$  and  $R$ , are equated to zero and the resulting equations solved for  $f^*$  and  $R^*$ . The optimum relationships are:

$$(5) \quad f^* = 3 \sqrt{\frac{Q^2 v_H c \pi r}{2M^2 (A_C)^2}}$$



$$(6) \quad R^* = 3 \sqrt[3]{\frac{2c^2 \pi^2 r^2 Q}{V_H \cdot M \cdot A_C}} .$$

Equation (2) may be interpreted as meaning that the optimum frequency (given the number of routes) is proportional to  $Q^{2/3}$  versus  $Q^{1/2}$  in the simpler route formulation. The optimum number of routes is proportional to  $Q^{1/3}$ . The traditional "square root rule" would tend to underdispatch buses because spatially-related user costs are not evaluated. Substituting  $f^*$  and  $R^*$  into equation (4) yields a surprisingly simple formulation of the optimum envelope of (generalized) total costs,  $TC^*$ , such that

$$TC^* = 3 \sqrt[3]{\frac{V_H c \pi r M A_C Q^2}{2}} + \frac{L v_v}{V} \cdot Q$$

or

$$TC^* = 3(\beta Q^2)^{1/3} + \frac{L v_v}{V} \cdot Q$$

where  $\beta = \frac{V_H c \pi r M A_C}{2}$ . The average (variable) generalized cost per trip is then

$$(7) \quad \begin{aligned} \frac{TC^*}{Q} &= \frac{3(\beta Q^2)^{1/3}}{Q} + \frac{L v_v}{V} \\ &= \frac{3\beta^{1/3} Q^{2/3}}{Q} + \frac{L v_v}{V} \\ &= 3\left(\frac{\beta}{Q}\right)^{1/3} + \frac{L v_v}{V} \end{aligned}$$

The marginal generalized cost is

$$(8) \quad \frac{\partial TC^*}{\partial Q} = 2\left(\frac{B}{Q}\right)^{1/3} + \frac{Lv_v}{V} .$$

This function graphed on the following page assuming the parameter values of the previous example with the additional assumptions that:

$c$  = cost per mile of pedestrian access = \$2.50

$\pi$  = .3.1416

$r$  = distance of average user from line-haul terminus = 1 mile

#### Perceived Cost Function for Integrated Services

Equation (5) relates the true total generalized cost to trip demand the other parameters and if an economy-wide marginal cost pricing regime is in effect, the price charged should be that given by equation (8). However, practical technological and political constraints on fare collection may tend to dictate a pricing scheme other than the optimal one. Generally, the agency costs perceived by the user (via a fare or other tariff) are not the true agency costs. Also, the user's perception of non-agency supplied inputs are those which are marginal to the user but which represent a social average. Thus the likely perception of generalized costs is equal to

$$(9) \quad \text{Fare} + 2\left(\frac{B}{Q}\right)^{1/3} + \frac{Lv_v}{V} ,$$

assuming that buses and routes continue to be optimally portrayed. Comparing equations (8) and (9), it appears that the fare on an optimally dispatched and routed integrated bus service should be zero in order to equate average perceptions and social (generalized)

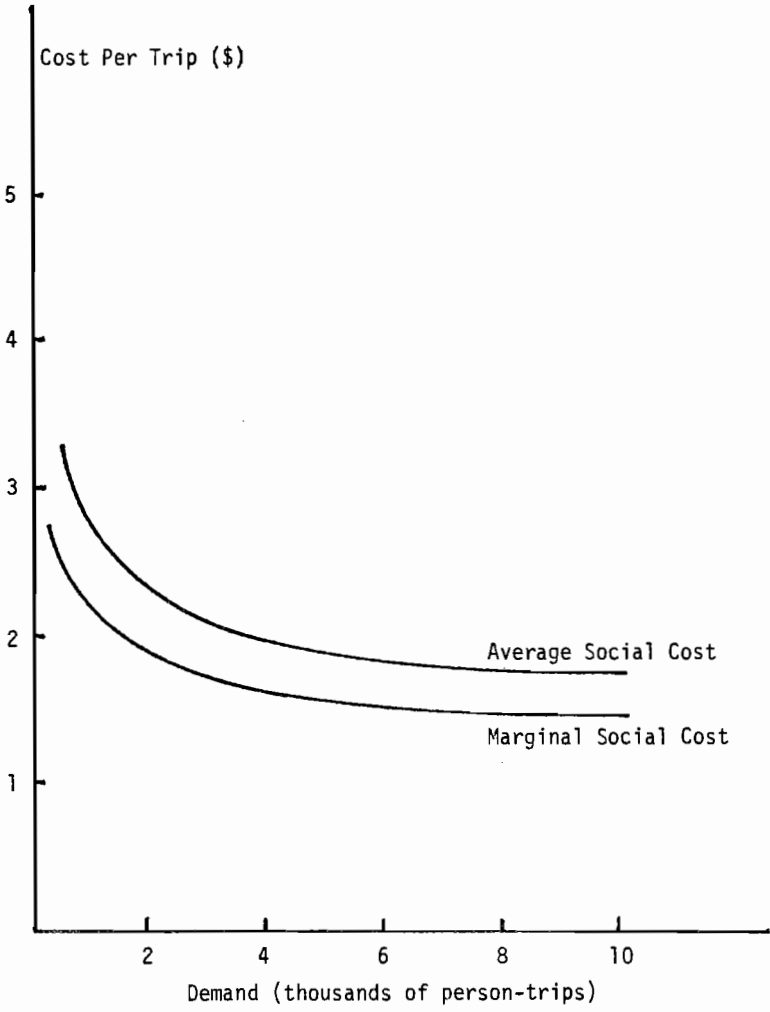


Figure 3: Integrated Bus Costs

marginal cost.

It is the functions in equations (8) and (9) that will be used in this study to model network costs.

CHAPTER FIVE  
THE COSTS OF MODERN FIXED RAIL RAPID TRANSIT

Although there exist fairly sophisticated analyses of the costs of providing urban transportation by the automobile or bus modes, there is a rather large void in the literature as to the costs of providing transit service on a fixed rail facility. Meyer, Kain and Wohl, in their classic work, do not develop any data on the relationship between costs and output in the rapid rail technology and present only sketchy evidence on the extent to which returns to density and returns to scale exist.

The scarcity of this type of information is obviously related to the scarcity of reliable observations on the cost of providing trip-making capacity by a rail technology. Few "modern" systems exist and the data that does exist is suspect for reasons to be discussed below. This chapter seeks to develop both the agency costs of providing rail rapid transit service and the user perception of these and other costs of trip-making on the mode. The agency costs are developed by both performing a longitudinal analysis of a month of recent BART experience and by a cross-sectional analysis of the recent experience of some other North American fixed-way properties.

Agency Costs -- The Costs of BART

The BART system is the most recent example of "modern" American rail technology and its costs are of special interest because the basic aesthetic and service configuration of the BART system\*

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\* I am referring to BART's high speeds, few station stops, and sub-urban to downtown urban service bias.

appears to be a model for the rail transit projects of some other American cities. While the analysis of the existing BART data is fraught with many basic difficulties, some reasonable assumptions and some careful analysis may permit us to develop some feeling for the short-run cost behavior of a BART-like system. Because the system has been only partially open and operating for barely a year,\* cost analyses must be performed cautiously to avoid inclusion of pre-operation types of expenses in operating cost estimates. These pre-operation expenses may be of several kinds. First, some of the expenses being incurred by the BART District are for capital equipment refinement rather than for true operations activities, yet these expenses appear in the cost accounts in operating expenses. Presently, the vehicles and the train control systems are undergoing substantial modification and redesign; these expenses should be isolated from "normal" maintenance and repair expenses to the extent that they are really capital investment activities rather than costs of current operations. In assembling expense data for the BART system, an attempt was made to isolate and identify

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\*The San Francisco Bay Area Rapid Transit District began revenue service on September 11, 1972 on a 26.5 mile portion of the 75 mile system. The headway between trains has varied with equipment failures, but is approximately ten minutes between the hours of daily service of 6 am and 8 pm. In January and May, 1973, 12.4 and 20 miles of additional track, respectively, were opened to service. The San Francisco to Daly City was opened in early 1974 and the scheduled opening of the transbay tube, at this writing, is September, 1974. A strike shut down the system for three weeks in July, 1973. The financial impact of the strike is included in the cost estimates of this report, although no attempt has been made to measure the duration (if any) of BART wage levels from true social cost of the labor. The data in this analysis is from the 9 month period of September 1972 to May 1973.

those accounts which were obviously not current operational expenses (such as warranted repair expenses on the vehicles or other equipment), but there is undoubtedly a considerable amount of activity on-going which involves capital-improvement activity that is not separable from operations expenses accounts.

Secondly, there is a certain amount of "learning" going on during the start-up phase of any production process which temporarily forces the enterprise to operate inefficiently. Estimates of the costs involved in some accounts made during the start-up period may thus overstate the true efficient costs of operation.

The relative youth of the system presents a fundamental data problem as well. While monthly expense data is available for all of the accounts of the system, there are too few stabilized observations on costs to permit a complete and rigorous time-series estimate of cost-output relationships, and there are too few distinct lines within the organization to permit cross-sectional analysis of the short-run cost functions.\*

The result is that a very brief data series is available for either statistical or accounting approaches to cost estimation. Certain accounts, such as maintenance of way and structures, maintenance of buildings and grounds, police services, station expenses, utilities, shop services, central operations control, and train attendant expenses were not considered to be "problem" accounts. Where certain irregularities in billing procedures could be discovered and worked out, the monthly data in these

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\* Although some expense data is available for each of the 4 lines, the allocation of expenses among the lines appears, in some cases, to be fairly arbitrary.

accounts was thought to have some use in a preliminary statistical analysis.

However, the accounts for support facility maintenance, electronic maintenance, rolling stock maintenance, line supervision, and, to a lesser degree, power facility maintenance all contain some pre-operation expenses in current cost estimates.

The aggregation and analysis of the various categories of expenditure is discussed below.

#### Maintenance of Way and Structures

Expenditures on the maintenance of way and structures probably pose the least difficulties analytically of any of the BART expense categories. Although the BART track gauge at 5'6" is wider than the standard 4'8-1/2", the basic technology of structures, tracking, and switches is not substantially different from that of other rail systems. Furthermore, there is probably less "breaking in" of the roadbed and structures because the system consists largely of rigid aerial and subterranean structures vs. the "soft" gravel roadbed which experiences a gradual settling. Much of the at-grade portion of the BART roadbed has been built on existing rail roadbed. All of these factors would tend to indicate that the current experience of the District in this category of expenses has stabilized somewhat.

The maintenance of way and structures is normally considered to be a direct function of the traffic using it. In the case of BART, the vehicle mileage is the appropriate independent variable; gross ton mileage could also be used, but since the vehicles are



all of the same approximate weight, vehicle mileage will produce the same relevant data.

As the dependent variable, the total of expenditures on track maintenance, switch and frog maintenance, yard track and switch maintenance, track inspection, structures maintenance and structures inspection should be used. While the monthly data is sparse and may contain spurious lags and variations that would not be noticeable over a longer period, regressing the monthly expenditures on way and structures maintenance (MMWS) against the monthly vehicle miles produced (VM) yielded the following results:\*

$$\text{MMWS} = \$42,594 + \$0.065 \text{ VM} \quad \text{in 1973 dollars}$$

$$(4842) \quad (.011)$$

$$R^2 = .85 \quad N = 9$$

$$DW = 1.3376$$

The result is certainly within the expected range given the experience of standard railroad operations. The incremental cost for maintenance of way and structures for standard rail passenger car traffic was estimated by Keeler to be \$.051 in 1968 dollars [49]. The \$.065 figure derived above is fairly reasonable given the substantial inflation that has occurred since 1968 and the higher standards of maintenance required by a high-speed BART-type vehicle. There is also some evidence that national roads (on which Keeler's estimates are based) are undermaintained.

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\*The assumption of a linear relationship between output (VM) and costs is, of course, a strong one, but sparseness of the data did not permit robust testing of alternative hypotheses. Work done in a later portion of this chapter, however, provides support for this assumption.

### Maintenance of Support Equipment

Much of the support equipment in the BART system is of fairly innovative design; this category includes electronic maintenance, power facility maintenance, computer maintenance, and general support facility maintenance. The train control equipment maintenance is included in this account (both the wayside and on-board components) and there has been a considerable amount of difficulty with this aspect of the BART system. Most of the warranty arrangements between BART and its equipment manufacturers are part-for-part exchange types of agreements, but BART generally bears some portion of the labor expenses required to replace or refurbish faulty components. Thus, these accounts probably contain a substantial (although indeterminable at this time) element of capital-improvement type activity, and a simple extrapolation to future output levels would probably substantially overstate BART's expenses in this category.

During the four-month period of December 1972 through March 1973, the maintenance expenses in these categories averaged \$214,000. Performing a regression between these expenses (MMSE) on the vehicle miles produced (VM) gave the following results:

$$\begin{aligned} \text{MMSE} &= \$141,534 + \$0.172 \text{ VM} && \text{in 1973 dollars} \\ & \quad (11,571) \quad (.024) \\ R^2 &= .88 && N = 9 \\ \text{DW} &= 1.806 \end{aligned}$$

Thus, although the vehicle miles produced increased over 2-1/2 times in this period, only about 33% of the expenses in this category appeared to vary with the use of the system, as would be a

reasonable proposition for equipment of this sort. In fact, two months before the operation of the system began, expenses in this category were approximately \$121,000 per month. Although the data is too sparse to be relied upon at this point, it seems to indicate that this account contains very large capital elements that are not properly included with normal maintenance expenses.

#### Maintenance of Rolling Stock

During the period of operation for which complete data is available (until May 1973), the BART vehicle fleet rose from 38 vehicles (36 "A" cars and 2 "B" cars) to 162 vehicles (105 "A" cars, 57 "B" cars).\*

BART practices a preventive maintenance program, bringing each car in once a month, whether there has been an equipment failure or not. In addition, at quarterly intervals, semi-annual intervals, and annual intervals other special monthly maintenance routines are appended to the monthly activities.

Currently it is anticipated that the scheduled maintenance routines will require the following man-hours of labor grade MMII [50]:\*\*

- (8) monthly maintenance routines: 22 man-hours each
- (2) quarterly maintenance routines: 30 man-hours each
- (1) semi-annual maintenance routine: 40 man-hours each
- (1) annual maintenance routine: 60 man-hours each

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\* These cars have been only conditionally accepted. The total of delivered vehicles is somewhat higher.

\*\* MMII labor receives, on average, about \$6.12 per hour plus an average 20% fringe (composed of a shift differential, over-time, holiday, pension, and FICA).

In addition to the scheduled maintenance expenses, it is roughly anticipated that approximately 40% of the scheduled maintenance expenses will be required additionally to perform unscheduled maintenance. Inspection is assumed to require 25% of the subtotal of all scheduled and unscheduled maintenance [51].

Janitorial maintenance of the vehicles is assumed to take approximately .5 man-hours daily per car. Materials consumption per vehicle per year is assumed to be approximately \$3500, making the total estimated annual maintenance expense per vehicle approximately \$8826 [52].

The current maintenance expense experience is substantially in excess of that "engineering" estimate. Both scheduled and unscheduled maintenance per vehicle is requiring, at least temporarily, a much greater level of activity. Unscheduled maintenance expenses in the month of May 1973 were nearly 400% of the scheduled maintenance expenses and the annual level of maintenance per delivered vehicle was approximately \$17,000 nearly twice the anticipated stabilized level [53].

Obviously if this level of expenses were to be bound into the maintenance of the vehicles without improvement, the implications for BART costs is substantial. There is good reason to believe, however, that the cars delivered by the manufacturer were not the pieces of capital that the rest of the system required, and that there is a substantial amount of maintenance activity that is, in fact, research and development and will eventually be eliminated from the costs of operating the system. The cars incorporate novel technology in nearly every aspect of their design; the

suspension system, braking systems, propulsion system, structural design and heating and cooling systems are all of fairly sophisticated design and have created operational problems at one time or another. (The train control system is not included in this category even though there are on-board devices; these expenses are aggregated with wayside and central electronic train control maintenance in the support equipment category above.)

The data, again, are insufficient to allow elimination of the capital elements of current operations expenses from the total maintenance expenses now being experienced by BART. Including in monthly rolling stock maintenance (MRSM) the expenses for preventive maintenance, unscheduled maintenance, vehicle cleaning, main shop maintenance and all other non-warranted expenses and regressing it against vehicle-miles produced (VM) in the same month illustrates the relative independence of the vehicle maintenance expenses and the usage of the vehicles, contrary to the traditional expectation. Undoubtedly a large portion of the "fixed" component of monthly rolling stock maintenance expenses is not strictly an operating expense.

$$\text{MRSM} = \$148,144 + \$0.169 \text{ VM} \quad \text{in 1973 dollars}$$

$$(21,770) \quad (.046)$$

$$R^2 = .66 \quad N = 9$$

$$DW = 1.892$$

#### Other Line-Haul Expenses

The other major line-haul expenses are traction power, line supervision, and central operations expenses. Traction power

expenses could be calculated from engineering data if the actual data were suspect, because the relationship between car-miles and the kilowatt-hours of energy consumption is known. The power charges have three components: a fixed facility charge, a demand charge and an energy charge. For traction power, the monthly demand charge is a function of the peak demands of the system and is \$1.44 per kilowatt. The energy charge is a function of the kilowatt hours consumed by the system and is \$.0048 per kilowatt-hour [54]. The vehicles are believed to consume 5.5 kilowatt-hours per car-mile [55], costing, on the margin, 2.6¢ per vehicle mile.

Central operations control expenses consist largely of wages and salaries for central control room personnel. The staffing of this activity is fairly independent of the level of output of the system. The account in this category of expenses which poses the greatest difficulty at this time is the line supervisory expenses which have been running nearly as much as the train operation (train attendant) expenses themselves. This is largely a result of the overstaffing necessary because of the poor functioning of the train control system. The line-supervisory expenses go in part to provide human backup to the system until the automatic train control system's fail-safe reliability can be demonstrated; this staffing has varied over the period studied.

The result is that this category of expenses is not significantly dependent upon the level of line-haul activities. These other monthly line-haul (OMLH) expenses regressed against vehicle-miles (VM) produced the following results:

$$\text{OMLH} = \$32,847 + \$.077 \text{ VM} \quad \text{in 1973 dollars}$$

$$(28.974) \quad (.061)$$

$$R^2 = .188 \quad N = 9$$

$$\text{DW} = 2.553$$

### Train Attendant Expenses

Train attendant expenses are a function of train-hours, the hours of system operation, train schedules and union work rules. The union regulations which govern BART train attendants require that 15-minute breaks be available to train attendants after each completed trip and at regular intervals throughout the day. At current levels of operation, the train attendant is paid for approximately 1.7 hours for every hour of actual platform duties. At higher levels of system output and when the system is operating the planned 20 hours per day, the ratio can be expected to change because of the potential of more efficient utilization of personnel.

Since the system operates at fairly constant average speed, the train-hour relationships can be translated into train-mile relationships. The table below gives the approximate cost of a train mile at the current level of labor utilization and the BART staff estimate of full system utilization:

<u>Output*</u>	<u>Cost/train-mile</u>
Current (2 million train-miles annually)	.53 [56]
Full stabilized service (6 million train-miles)	.50 [57]

Thus the costs per car-mile, dependent upon the length of the train,

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\*Throughout this report, "current" refers to the latest month for which output data was available at this writing (May 1973) and full system output refers to the 1975-1976 expected output.

are the following:

<u>Output</u>	<u>Cost/vehicle-mile</u>
Current (8 million car-miles annually)	.131 (4 cars)/.053 (10 cars)
Full system (25 million car-miles annually)	.126 (4 cars)/.046 (10 cars)

The full system service level is assumed to be the following on each of the lines [58]:

	<u>Average Headways</u>			
	Fremont-Richmond	Concord-Transbay	Richmond-Transbay	Fremont-Transbay
<u>Weekday</u>				
5am-9am	6 min.	6 min.	6 min.	6 min.
9am-3pm	12	12	12	12
3pm-7pm	6	6	6	6
7pm-10pm	12	12	12	12
10pm-1am	20	20	20	20
<u>Saturday</u>				
5am-10pm	15	15	15	15
10pm-1am	20	20	--	--
<u>Sunday</u>				
5am-10pm	15	15	--	--
10pm-1am	20	20	--	--

### Station Expenses

In standard rail and bus operations, a considerable amount of station expenses are variable with the total patronage of the system. The BART system has relied upon automated dispensation of tickets, change-making and turnstile operation. Thus the passenger handling capacity of the personnel in the stations is quite high. A station agent's activities in the BART system consist mainly of monitoring activities, making sure that the system



is not abused by violators, providing access to the restrooms, and providing general surveillance of the ticketing process and patron movements within the station.

A large station may have two station agent "centroids" manned for the entire operation period of the station. The full system is expected to require 174 full-time station agents for round-the-clock (20 hours) manning of the 34 stations. This implies slightly over two agents per station at all times [59].

Other expenses of station operation include station lighting and heating, station and office janitorial services, expenses for station, office and grounds maintenance. The expenses of turn-stile maintenance are included in the category of support facility maintenance.

On the portion of the system that is now open (24 of the 34 stations are now operating), station expenses have totalled approximately \$11,000 per month per station.

Although there would be some variation expected in station expenses at various patron loads, mainly in the maintenance categories, these services are contracted and have been effectively fixed over the period of operation. Given the type of technology that is employed at the stations, the assumption that the station expenses are fixed over a wide range of outputs is probably not an unreasonable one and will be employed here.

#### General Traffic and Administration

To a substantial degree, the current level of administrative expenditures includes planning activities that are oriented toward

future extensions of the system and on-time revisions of early planning of the operation of the system. What is relevant for an estimate of the stabilized costs of providing various outputs of the system, however, are only those activities directly related to the planning and execution of current operations. Certain expenses related to expansion of the system may be easily separated from current operating expenses. Most of the non-operating or pre-operating expenses, however, are not easy to identify because they involve portions of individuals' effort and no logging of this activity is available.

Included in the general category, however, are:

- Police services
- Shop services (mainly staff automobile maintenance)
- General managers office
- District secretary
- Legal department
- Treasury department
- Controller's department
- Systems and data processing
- Personnel department
- Labor relations department
- General services and stores
- Public relations department
- Office of planning
- Office of research
- Engineering department
- Real estate department
- Operations management
- Management of transportation, rolling stock, power and way
- Operator training expenses
- Vehicle acceptance testing

Currently, costs in this category have risen from an annual level of \$10,500,000 in September 1972 to \$15,900,000 in May 1973.\* An estimate of the stabilized level of these expenses performed by

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\* Because of the difference in the way the reports which contain this data are structured, these expenses are measured as a residual of the total monthly expenses and the estimate of all other cost categories obtained in the expense reports.

BART itself estimated the annual expense in these categories at about \$11,600,000 in 1973 dollars [60].

### Capital Costs

None of the above expense categories have included any allowances for depreciation of the basic capital plant. The capital costs are calculated separately here.

Vehicle Capital Costs. As of July, 1972, the estimated total purchase price of the first order of 250 cars was \$79,860,000 or approximately \$320,000 per vehicle [61]. While there has been considerable inflation in the market for this type of equipment, this figure also includes the amortizing of development costs and so is not an unreasonably low estimate of current replacement cost.

Assuming that the vehicle is of approximately constant productivity over a 25 year life, and at full operation will travel approximately 100,000 miles per year, the following costs of the vehicles can be derived:

Average vehicle cost = \$320,000

Annualized capital cost @ 6% = \$25,034; @ 12% = \$40,797

Annual capital cost/vehicle mile @ 6% = \$.25; @ 12% = \$.41

Other Plant and Equipment Capital Costs. An estimate of the total accumulated capital cost of the other plant and equipment in the BART system is available in BART Comparative Data Reports. This probably overstates the current book value of the plant somewhat, but would be less than the current replacement value of the plant and equipment; also, insofar as some of the contracts are

incomplete, if the projected completion costs were used the figures would be given another upward bias. Also, as has been mentioned with respect to some other categories of costs, there are a considerable number of capital improvement/refinement activities still going on. There is also some question whether or not BART paid above the market price for plant and equipment.\*

The estimated completion cost of the total system in July 1972 was \$1,345,892,000 excluding vehicles but including pre-operating expenses estimated at that time; given the uncertainty of the dimension and net effect of the factors mentioned above, this figure will be used as an estimate of capital cost for plant and equipment.

The composition of these expenditures were as follows:

Track and structures	\$640,413,000
Stations	246,895,000
Yards and shops	20,027,000
Electrification	35,224,000
Train control	40,796,000
Utility relocation	43,180,000
Engineering and charges	125,745,000
Right-of-way	97,247,000
Contingencies	20,522,000
Non-allocable	38,802,000
Pre-operating expense	37,041,000

Assuming constant depreciation over the life of the system and assigning a 50 year life to structures and an infinite life to rights of way, the capital costs are estimated to be as follows:

Total system cost (excluding vehicles) = \$1,345,892,000  
 Annualized capital costs @ 6% = \$85,048,800; @ 12% = \$162,031,470  
 Annual capital cost/vehicle mile @ 6% = \$3.35; @ 12% = \$6.39  
 (assuming 25,350,000 vehicle-miles annually)

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\* BART often found itself with fewer bidders on contracts than would have been desirable. Also, an internal system of cost controls was not in effect for the first 4 years of construction activity.

### Unit Cost Calculations for BART Service

Seat-mile and car-mile calculations may be made from the above data. Given the uncertainty of the dimension of learning and capital costs which may be "hidden" in the current cost accounts, it is probably better at this time to present a range of cost estimates rather than make a precise statement.

Three estimates will be employed here. The first is based upon the data and analysis presented above. The second takes the average cost experience of recent actual experience and assumes that these average unit costs will prevail at future levels of operation. Finally, BART itself made what might be called "engineering" estimates of its costs of operation for budgeting purposes. Although capital costs were not presented in their material, I have included the above capital cost calculations in the BART-based estimate.

The table following presents the average cost per seat-mile for several levels of output, in 1973 dollars.

	Estimate <sup>*</sup> 1	Estimate <sup>**</sup> 2	Estimate <sup>***</sup> 3
<u>Average capital cost</u>			
5,000,000 car-miles	\$ .236	\$ .236	\$ .236
10,000,000 car-miles	.118	.118	.118
25,000,000 car-miles	.047	.047	.047
<u>Average operating cost</u>			
5,000,000 car-miles	.0306	.0722	.090
10,000,000 car-miles	.0306	.0411	.045
25,000,000 car-miles	.0306	.0218	.021
<u>Average total cost</u>			
5,000,000 car-miles	.2666	.3082	.556
10,000,000 car-miles	.1486	.1591	.163
25,000,000 car-miles	.0776	.0688	.068

\* Extrapolation of May 1973 average unit costs @ 6%, adjusted for strike impact.

\*\* Use of time series analysis of monthly costs @ 6%, adjusted for strike impact.

\*\*\* Based upon BART staff budget estimate, adjusted for strike impact [62].

It is obvious from this analysis that the capital costs predominate in the total seat-mile cost figures. While the BART budget estimate is fairly close to the estimate produced by the analysis presented in this paper, if the future cost experience of BART behaves in an average fashion as it has behaved in BART's early operation, the implications for BART's early operation, the implications for BART's financial viability are nonetheless not inconsequential. The BART system is obligated to finance its operating costs out of the farebox. The current level of fares was considered to be a break-even level if costs behaved as in estimate 3 prior to the strike. The implication for BART if costs behave as in estimate 1 is that there will be an additional deficit of \$15,300,000 annually. The impact of the wage agreement is to increase operating cost by \$3,780,000 annually. The statistical relationships developed above may also be summarized in the form of short run cost functions. Table 10 shows the development of the relationship between annual operating costs and the annual output of the BART system.

As Table 10 reveals, the short-run marginal costs of operation of the BART system are roughly \$.75 per vehicle mile\* or about a cent per seat-mile, since each car has 72 seats. It is not clear from the kinds of limitations under which a new system like BART operates whether these cost estimates are to be relied upon. Furthermore, since the data exists only for one system scale, there is no means of developing a long-run cost function for the rail technology. While the BART technology is unique in many

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\* 
$$SRMC = \frac{\partial SRTC}{\partial Q} = \$.753$$

Table 10

Summary of BART Operating Cost Relationships

Annual maintenance of way and structures =

$$12 \times 42,594 + .065 \text{ VM} = \$ 511,128 + .065 \text{ VM}$$

Annual maintenance of support equipment =

$$12 \times 141,534 + .172 \text{ VM} = 1,698,408 + .172 \text{ VM}$$

Annual maintenance of rolling stock =

$$12 \times 148,144 + .169 \text{ VM} = 1,777,728 + .169 \text{ VM}$$

Other line-haul expenses =

$$12 \times 32,847 + .077 \text{ VM} = 394,164 + .077 \text{ VM}$$

Train attendant expenses =

$$0 + .046 \text{ VM} = 0 + .046 \text{ VM}$$

Station expenses

$$12 \times 34 \times 11,000 + 0 \text{ VM} = 4,488,000 + 0 \text{ VM}$$

General traffic and administration =

$$\underline{\$11,600,000 + 0 \text{ VM} = 11,600,000 + 0 \text{ VM}}$$

1) Total Annual Operating = \$20,469,428 + .529 VM  
Costs

$$\begin{array}{l} \text{Total Annual Operating} \\ \text{Costs in million of} \\ \text{dollars with VM in} \\ \text{millions of car-} \\ \text{miles (Q)} \end{array} = 20.47 + .529 \text{ Q}$$

2) Annualized way and  
structures costs  
(@ 6%) in millions  
of dollars = 85.05 + 0 Q

3) Average increment of  
annualized vehicle  
capital (@ 6%) = 0 + .25 Q

4) SRTC = Total Annual  
BART costs in  
millions of dollars = 105.52 + .753 Q

respects, it surely belongs to the family of rail transit technologies and some insight into the reliability of these longitudinal cost estimates may be gained by analyzing a cross-section of other properties.

#### Agency Costs -- Cross Sectional Study

The analysis of the cost and operating experience of some North American rail transit properties may shed some light on the extent to which the results of the BART costs are unusual because of learning expenses or otherwise atypical of rail transit costs experienced elsewhere. Data on the operating costs and production of the North American rail transit properties is available from annual reports filed with the American Transit Association and elsewhere [ 63 ]. These costs generally include maintenance, operator's wages, the salaries of other transit personnel, power expenses, taxes, materials and other expenses incurred in production of transit services. Capital costs are sometimes presented in the form of depreciation and interest on capital equipment such as cars and track structures. This accounting valuation of equipment is inadequate from the standpoint of economic analysis because of the varying procedures used to depreciate capital equipment and the poor correlation between economic and book values. Much of New York City's system, e.g., is carried at zero book value in spite of its obvious economic productivity and high replacement cost. Thus the only reliable data are on operating expenses and independent measures of capital cost must be sought. While such a capital cost series might be developed from a careful inventory of transit equipment, the valuation of this inventory proves difficult because



of the lack of active markets in much of the pieces of capital and the wide valuations in the types of capital used. However, we have accurate capital cost estimates for the system (BART) that we are considering.

The work of Klein [ 64 ] and Keeler [ 65 ] in electricity production and standard rail operations, respectively, suggests that a regulated industry must take production to be exogenously determined and that the agencies then seek, within this constraint, to minimize total costs. In the context of rapid rail operations, this interpretation would mean that the transit agency is asked to provide the urban population with a certain trip-making capability. Thus certain "trips" are the obvious units of output which the agency seeks to provide, but within a particular urban environment. This demand for trip-making capacity is probably correlated with another, more tractable, output unit, the vehicle-miles produced. Thus, while the agency is ultimately concerned with satisfying given trip-making demands (and will seek to minimize the vehicle-miles required to produce these trips) its ultimate decision variable is vehicle-miles.

If it can be supposed that the relationship between vehicle-miles and the inputs of capital labor take the following form of a generalized Cobb-Douglas production function,

$$(1) \quad Q = AK^b V^{b_1} L^{b_2} E^{b_3} b_4$$

where  $Q$  is annual output in vehicle-miles

$V$  is number of vehicles

$K$  is miles of single track

L is number of units of transit labor

E is electricity

and that the agency seeks to minimize total costs, C,

$$(2) \quad C = P_K K + P_V V + P_L L + P_E E$$

and where  $P_V$  is the economic rental cost of vehicle

$P_K$  is the economic rental on track

$P_L$  is the labor wage

$P_E$  is price of electricity

then short-run total costs (SRTC) can be determined by minimizing

(2) subject to the production function (1) as a constraint to determine the variable factor-demand equations which, upon substitution in (2), yields the SRTC function. Since track is not variable in the short-run, this substitution yields a function of the form

$$(3) \quad \text{SRTC} = a_1 K + \gamma P_V^{a_2} P_L^{a_3} P_E^{a_4} Q^{a_5} K^{a_6}$$

$$\text{where } \gamma = \left[ \frac{b_3 b_4}{(b_3 + b_4)} \right]^{-1/b_2 + b_3 + b_4} + \left[ \frac{b_2 b_4}{(b_2 + b_4)} \right]^{-1/b_2 + b_3 + b_4} + \left[ \frac{b_2 b_3}{(b_2 + b_3)} \right]^{-1/b_2 + b_3 + b_4}$$

$$a_1 = P_T$$

$$a_2 = b_2 / b_2 + b_3 + b_4$$

$$a_3 = b_3 / b_2 + b_3 + b_4$$

$$a_4 = b_4 / b_2 + b_3 + b_4$$

$$a_5 = 1/b_2 + b_2 + b_4$$

$$a_6 = -b/b_2 + b_3 + b_4$$

As Keeler points out [ 66 ],  $P_K$  includes not only the economic rental value of track and structure, but also some components of operating cost that are fixed in the short-run.

In the actual estimation of (3), several modifications were necessary. First, since a reliable capital series for track and structures was not available for the reasons mentioned above, (3) was estimated using operating cost data alone. The coefficient estimated in place of  $P_K$  in (3) was then only the fixed track-related component of operating expenses. Second, the price of vehicles,  $P_V$ , was very difficult to obtain for the same reason and was dropped from the formulation. The basic formulation estimated for short-run operating costs (SROC) was then

$$(4) \quad \text{SROC} = P'_K + \gamma P_L^3 P_E^4 Q^5 T^6 .$$

The data consisted of 105 observations over 11 years on variously 8 to 11 properties.\* Since (4) is a non-linear form, ordinary

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\*The properties included in the sample were operated by the following organizations:

Metropolitan Transportation Authority  
 Chicago Transit Authority  
 Massachusetts Bay Transportation Authority  
 Toronto Transit Commission  
 Southeastern Pennsylvania Transportation Authority  
 Montreal Urban Transit Commission  
 Port Authority Trans-Hudson  
 Cleveland Transit System  
 Port Authority Transit Commission (Lindenvold)  
 The City of Shaker Heights Department of Transportation  
 Public Service Coordinated Transit of Newark

least squares estimation was not applicable except in a modified form in which  $P_k^i T$  (using trial values of  $P_k^i$ ) is subtracted from both sides and a log-linear form is estimated using supplied values of  $P_k^i$ . The trial values of  $P_k^i$  were varied in order to seek a minimum sum of squared residuals. Solution of the  $P_k^i$  which minimized the sum of squared residuals yielded very plausible estimates of the other parameters (see Table 11, Model 1) and the implied multiplicative error structure seems more reasonable than the additive error structure ultimately estimated, but because of other problems (see below), this method of estimation was abandoned. A non-linear Gauss-Newton form of estimation of (4) was also tried. This method, which requires preliminary parameterization of the estimated equation and proceeds to select new values of the parameters which minimize the sum of squared residuals [ 67 ], yields similar estimates, but the residuals of this formulation displayed substantial heteroskedasticity, unlike the log-linear estimation. The residual structure also seemed to display a bias in estimation which overestimated costs of small agencies and underestimated costs of the largest agency (NY). It seemed reasonable to suspect that the fixed component of operating expenses varied with the type and complexity of the system so the observations were broken up into 3 groups,\* consisting of a group of properties with lighter rail equipment (trolley-type weight equipment), a middle group of properties with standard subway-type equipment and a third group consisting of NYC by itself because of the sheer

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\*For a more substantive presentation of the tests of homogeneity of the population, see Merewitz and Pozdena, "A Long-Run Cost Function for Rail Rapid Transit Properties," Working paper, Transportation Cost Study, Institute of Urban and Regional Development, Berkeley, 1974.

size of the property. The estimated equation was then of the form

$$(5) \quad \text{SROC} = (r_1 + r_2 S + r_3 M) K + \gamma' P_L^{a_3} P_E^{a_4} Q^{a_5} T^{a_6}$$

where  $S$  is a dummy variable which takes the value of 1 if the property is in the smallest group, 0 otherwise,

$M$  is a dummy variable which takes the value of 1 if the property is in the middle range of properties, 0 otherwise.

The hypothesis maintained was that  $r_2 < r_3 < 0 < r_1$  because of basic technological differences among the groups.\* The results of estimation of equations (4) and (5) are as shown in Table 11 as Models 2 and 3 respectively. Equation (5) is significantly different from equation (4) at the 5% level of confidence.

The economic interpretation of these results is displayed in Table 12. It should be noted that the estimates  $\alpha_5$  indicate that there are approximately constant unit variable costs in the short-run. See the note on Table 12. Parameterizing the estimated forms of equations (4) and (5) using the dimensions and factor prices of the BART system in 1973 dollars, the various models produce the following short-run operating cost (SROC) functions. For purposes of comparison, Table 13 contains the short-run operating cost function estimated earlier in the chapter from BART-specific data. That estimate is certainly a reasonable one (and the realism of the assumption that the exponent of  $Q$  was 1.000 seems to have

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\* New York (10 times as large as the next largest property) was one "group", light rail systems made up another group and the remainder made up the "middle" group.

Table 11

## Estimated Parameters of Short-run Cost Function

Statistic	Model	Model	Model
	1	2	3
$P'_K$	.110 (—)	.049 (.019)	--
$r_1$	--	--	.165 (.022)
$r_2$	--	--	- .133 (.021)
$r_3$	--	--	- .053 (.016)
$\gamma'$	7.885 (2.166)	8.143 (4.062)	4.950 (2.623)
$\alpha_3$	1.343 (.270)	1.090 (.117)	1.709 (.203)
$\alpha_4$	.652 (.1180)	.584 (.083)	.571 (.084)
$\alpha_5$	1.042 (.0660)	1.152 (.1396)	1.266 (.143)
$\alpha_6$	- .368 (.092)	- .366 (.158)	- .595 (.164)
$R^2$	.915	.9505	.9697
SSR	22.56	1.468	.9009
N	105	105	105

Note: The equations of Models 2 and 3 were estimated after correcting for heteroskedasticity by multiplying both sides of the equation by  $T^{-.25}$ . The numbers in parentheses are the standard errors of the estimates.

Table 12

	Model 1	Model 2	Model 3
Threshold annual operating costs per mile of single track	\$110,000	\$ 49,000	\$165,000 (NY) \$112,000 (medium) 32,000 (small)
Economies of density ( $1/\alpha_5$ )	.960	.868	.79

Note: While the estimates of  $\alpha_5$  indicate that a true value of this parameter greater than 1.0 cannot be statistically rejected with great confidence, we will assume a value of 1.0 in subsequent material because it facilitates later analysis and provides, if anything, a bias in favor of rail transit; this is a logical stance we will pursue throughout this research.

Table 13  
Estimated Operating Cost Functions

Model 1

$$\begin{aligned} \text{SROC}_1 &= .110 T + 7.885 P_L^{1.343} P_E^{.652} Q^{1.042} T^{-.368} \\ &= .110 T + 4.19 Q^{1.042} T^{-.368} = 16.5 + .663 Q^{1.042} \end{aligned}$$

Model 2

$$\begin{aligned} \text{SROC}_2 &= .049 T + 8.143 P_L^{1.090} P_E^{.584} Q^{1.152} T^{-.366} \\ &= .049 T + 3.86 Q^{1.152} T^{-.366} = 7.35 + .610 Q^{1.152} \end{aligned}$$

Model 3\*\*

$$\begin{aligned} \text{SROC}_3 &= .112 T + 4.950 P_L^{1.709} P_E^{.571} Q^{1.266} T^{-.595} \\ &= .112 T + 6.93 Q^{1.266} T^{-.595} = 16.8 + .352 Q^{1.266} \end{aligned}$$

From 1973 BART data

$$\text{SROC}_4 = (\text{from Table 10}) = 20.47 + .529 Q^{1.000}$$

where

$P_L$  = \$5.34/hr = base wage of train attendants\*

$P_E$  = \$.012/kwh = price of electricity\*

$T$  = 150 miles = single track in BART system

$Q$  = annual level of output in millions of vehicle-miles

SROC = annual operating costs in million of dollars

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\* Source: Inter Office Memo, SFBARTD, R.C. Snyder to W.C. Hein, March 13, 1973.

\*\* It is assumed that BART is a "medium" property.

been borne out by this cross-sectional analysis), but the other models consistently demonstrate a smaller fixed component of these expenses than the direct BART estimate implies. This may be a manifestation of the capital refinement activities going on in the BART system. The total operating costs at 25,000,000 annual vehicle-miles implied by the various models all lie in the range of \$32-\$38 million, however, as Table 14 reveals.

Table 14

Estimated Annual Total BART Operating Costs  
At 25 Million Annual Car Miles

Estimate 1:	\$35.5 million; Implied by Model 1
Estimate 2:	\$32.2 million; Implied by Model 2
Estimate 3:	\$37.5 million: Implied by Model 3
Estimate 4:	\$33.7 million: Implied by BART experience
Estimate 5:	\$37.8 million; BARTD's estimate, corrected by author for strike impact

Thus BART seems to be operating within an order of magnitude of other such systems in North America. BART's technology was originally conceived of as one which would economize on operating costs at the expense of fairly lavish capital outlays. To the extent that BART is not using some of the most important components of its labor-saving technology (it has had additional supervisory personnel backing up the computerized train control), some savings are certainly realizable. From the evidence compiled in this portion of the chapter, there is no means of assessing these potential cost savings, but we do know that BART's operating cost experience



does not now differ significantly from that of other systems in North America. For the remaining purposes of this present work, the results of Model 1 will be used to estimate the short-run agency cost functions for a BART-like system. Using the way and structures and vehicle capital cost assumptions made in Table 10 above, short-run total costs become

$$\begin{aligned} \text{SRTC} &= .110 T + 4.19 Q^{1.042} T^{-.368} + .25 Q + 85.05 \\ &= (.110 + \frac{85.05}{T}) T + 4.19 Q^{1.042} T^{-.368} + .25 Q \\ &\cong .677 T + .913 Q^* \end{aligned}$$

#### User Costs and Total Perceived Costs

The costs to the users of rapid rail service consists of their perception of agency costs (that is, a fare or other tariff) plus their valuation of in-vehicle time, waiting time, access time and transfer time. The derivation of the components of the user-perception of trip costs is similar to that followed in the previous description of bus costs.

#### Assuming Pricing at Social Cost

For a route of length  $M$  miles and an average service speed of  $V$ , the headway  $H$  between trains is

$$H = \frac{2M}{V}$$

---

\*The exponent of  $Q$  has been approximated by 1.000 to simplify the later analysis requiring disaggregation of routes. This will tend to bias the analysis in favor of the rail transit alternative.

implying a service frequency  $f$  (in trains per hour) of

$$f = \frac{1}{H} = \frac{V}{2M} .$$

The total agency cost of service on the route is then

$$\alpha f = \alpha \frac{V}{2M}$$

where  $\alpha$  is the round-trip cost of rail service, which depends on service speed and the vehicle-mile costs of the service. The average user time spent in the vehicle is a function of the average trip length,  $L$ , and the speed of service

$$t = \frac{L}{V}$$

with a perceived value of  $tv_v$  where  $v_v$  is the value of in-vehicle time in \$/hour.

The value of the time that the user spends waiting between trains is assumed, as in the bus mode, to be one-half the headway on the average; the perceived cost to the user is then  $v_H \frac{H}{2}$ .

The perceived costs of feeder services to and from the rail line-haul are likely to be higher for the fixed rail system than for an optimally routed bus system because of the greater average distance of residences and work places from transit stops. The results depend fairly strongly on data about residential and work-place densities, and assumptions about the features of the service area. Furthermore, the existence of a transit line may have long-run consequences on residential and work place location that would be dealt with in a transportation/

land-use feedback that such wide optimization processes do not allow. Thus here the simpler (and generous to rail) assumption is made that the feeder and distribution distance for rail transit are only twice that of the bus mode. If the value of walking time is roughly 3 times that of in-vehicle time and a man walking moves at 4 mph vs a bus at 12 mph, this may be interpreted as meaning that the average potential transit user has to walk 1 mile total in access to and egress from the rail facility or that he takes feeder buses for roughly 4 miles in total. Additionally, a cost of transferring from a feeder or distribution mode is incurred in completing a trip by the rapid rail mode. Some studies have established an implicit value of the transfer of \$.15/transfer in 1970 dollars [68]. Or the transfer may be viewed as an increment of waiting time. At a value of waiting time of \$3/hour, the \$.15 transfer may be interpreted as having a value equivalent to 3 minutes of waiting time. Generally we assume, conservatively that the transfer cost,  $T$ , equals \$.15. As detailed in the previous section of this chapter, the short-run costs of a trip by rail transit are a function of the scale of the system (total track mileage,  $k$ ) and the intensity of the use of the system measured by vehicle miles,  $\phi$ . That is, total supplier costs  $C_S$  were shown to include a component which was fixed with respect to vehicle miles and one which was variable with output as in Equation (6).

$$(6) \quad C_S = C_S(\phi, k) = \beta_1 k + \beta_2 \phi^{Y_1} k^{Y_2} .$$

In order to decompose those system costs into route costs, two assumptions must be made:

- 1) that the fixed costs are proportional to track (and hence, route) length and
- 2) that the variable costs are homogeneous of degree 1 in output.

Both of these assumptions are borne out in the discussion of the previous section. Then the fixed cost component of the model of short-run total costs summarized in equation (5)  $\beta_1 k$  is, in fact, proportional to track length. The variable cost component,  $\beta_2 \phi_1^{\gamma_1} \phi_2^{\gamma_2} k^2$ , can be considered homogeneous to degree one if  $\gamma_1$  is equal to 1. As the discussion of the statistical estimation of the previous section illuminates, it is not possible to statistically distinguish the exponent of vehicle-miles from 1. We will assume for the purposes of the route-cost analysis that this exponent is identical to 1.0. Thus if a rail transit system consists of two distinct and non-overlapping routes of length  $k_1$  and  $k_2$  respectively and

$$k_1 + k_2 = k,$$

the agency costs on each of these routes are presumed to be  $C_{s1}$  and  $C_{s2}$  respectively where

$$\begin{aligned} C_{s1} &= \beta_1 k_1 + \beta_{21} \phi_1^{\gamma_1} k_1^2 \\ C_{s2} &= \beta_1 k_2 + \beta_{22} \phi_2^{\gamma_2} k_2^2 \end{aligned} .$$

where  $\phi_1$  and  $\phi_2$  are the vehicle-miles produced on each route.

Obviously if the routes overlap, the fixed component of costs would be overstated. The pricing regimes analyzed in this present work (marginal cost pricing and existing fare pricing) are not affected by this result, however. The total costs of providing rail service on an imaginary, independent route of length  $M$  miles and patronage density of  $Q$  patrons per hour is

$$\begin{aligned}
 C &= \text{agency costs} + \text{value of in-vehicle time} \\
 &\quad + \text{value of waiting time} \\
 &\quad + \text{value of access and egress time} \\
 &\quad + \text{value of transfer} \\
 &= \text{agency costs} + \frac{QLv_v}{V} + \frac{Qv_H}{2f} + Q \cdot w + Q \cdot T
 \end{aligned}$$

where  $f$  is the frequency of service in (evenly spaced) trains per hour.

The agency costs consist, as detailed above, of the fixed and variable expenses necessary to provide train service at the frequency of  $f$  per hour. The total agency costs per hour then of supplying this route with service are

$$\text{agency costs/hr} = \text{fixed costs/hr} + \alpha f$$

where  $\alpha$  is the variable cost of a train-trip of length  $M$ . Thus

$$\begin{aligned}
 \alpha &= \text{variable cost/train-hr} \cdot \frac{M}{V} \\
 &= \text{variable cost/train-mi} \cdot V \cdot \frac{M}{V} \\
 &= (\text{variable cost/veh-mi}) \cdot (\text{vehicles/train}) \cdot M \\
 &= \text{AVC} \cdot M \cdot P
 \end{aligned}$$

where  $P$  is the number of cars per train.

The time spent in the vehicle by the average user depends on the average trip length (here presumed to be one-half the route length) and the average service speed of the train. Then the total social cost per hour,  $C$ , of providing  $Q$  patrons on this route with rail transit service is

$$C = \text{route fixed costs/hr} + M \cdot \text{AVC} \cdot P \cdot f + \frac{Q L_V}{V} + \frac{Q v_H}{2f} + Q \cdot w + Q \cdot T$$

assuming one transfer per trip.

Optimizing the frequency of service  $f$  to minimize  $C$  yields a "Mohringesque" square root rule of dispatch where

$$\bar{f} = \sqrt{v_H Q / 2M \cdot \text{AVC} \cdot p}$$

From the first part of this chapter, the fixed cost per route-mile/hr,  $F$ , may be calculated. The minimum social cost of providing the  $Q$  trips is then

$$\begin{aligned} \bar{C} &= FM + M \cdot \text{AVC} \cdot P \cdot \bar{f} + \frac{Q \cdot L_V}{V} + \frac{Q \cdot v_H}{2\bar{f}} + Q \cdot w + Q \cdot T \\ &= FM + \sqrt{2 \cdot M \cdot \text{AVC} \cdot P \cdot v_H \cdot Q} + Q \cdot \frac{L_V}{V} + Q \cdot w + Q \cdot T \end{aligned}$$

where  $F$  is the hourly fixed costs of the route/mile. Note that  $p$ , the number of cars per train, has not been specified. Generally,  $p$ , like  $f$ , is a variable which is in the agency's control and an optimum train length should be determined interactively with train frequency. This might entail, for example, selection of  $p$  in order to minimize  $\bar{C}$  subject to the constraint that

$$\bar{P} \cdot S \geq Q/\bar{f}$$

where  $S$  is the number of seats per vehicle. That is, the seating capacity must be at least as great as the average patron demand for this capacity per train.\* In the case of BART, however, the technology does not permit convenient changing of train length during different periods of the day. The trains require a special "A" car at each end of the train, so a train cannot be simply split, but must be assembled. Depending upon siding and yard costs and capacity, at some point it would become feasible to assemble trains rather than inflict additional wear-and-tear on the vehicles. At this time, however, BART is planning to run trains of a 10-car length continuously throughout the day. Thus  $P$  is assumed equal to ten through the remainder of this analysis.

The average social cost per user is

$$\bar{c} = \frac{FM}{Q} + \sqrt{\frac{2M \cdot AVC \cdot P \cdot V_H}{Q}} + \frac{L v_V}{V} + W + T \quad .$$

The marginal social cost is

$$\frac{\partial \bar{c}}{\partial Q} = \sqrt{\frac{M \cdot AVC \cdot P \cdot V_H}{2Q}} + \frac{L v_V}{V} + W + T \quad .$$

Note that both average and marginal social cost tend asymptotically to  $\frac{L v_V}{V} + W + T$  as  $Q$  becomes very large.

These short-run cost relationships are graphed on the following page using the values of the parameters as given in Table 15.

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\*This assumes that the standard of service of one seat per patron is a binding constraint.

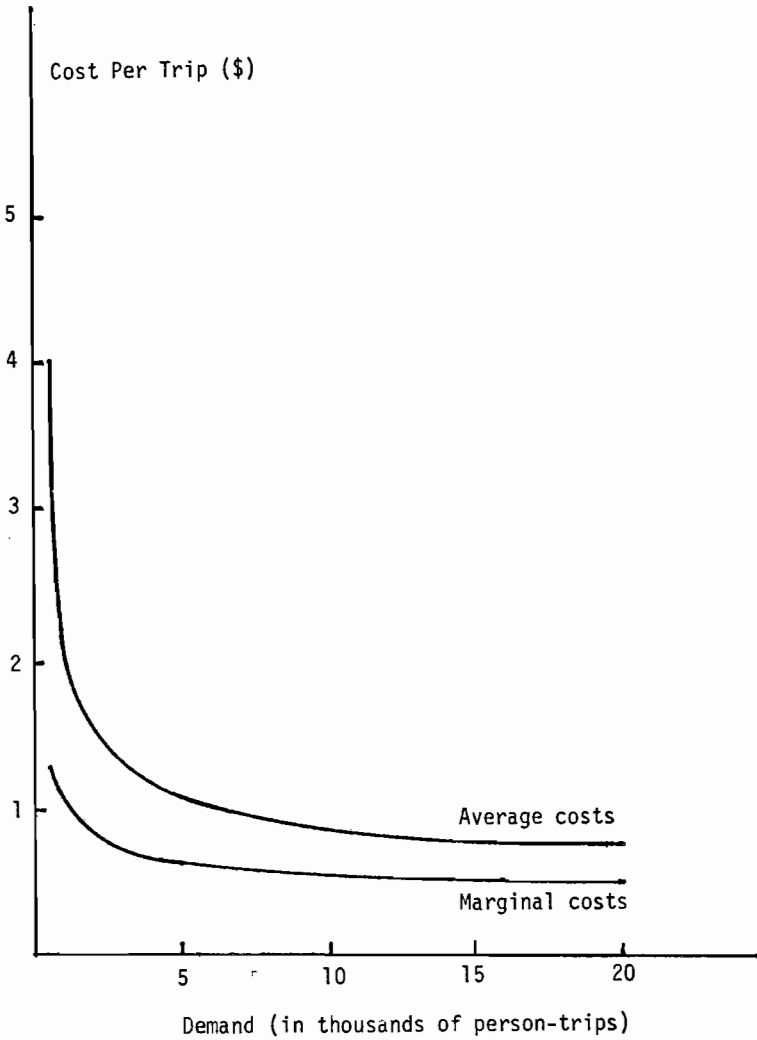


Figure 4: Rail Line-Haul Costs



Table 15

$L$  = average trip length = 5 mi  
 $M$  = route length = 10 mi  
 $w$  = average access cost = \$.40  
 $w$  = base wage of transit operators = \$5.34  
 $P_E$  = price of electricity in \$ per kwh = \$.012  
 $V$  = average service speed = 40 mph  
 $V_V$  = value of in-vehicle time in \$/hr = \$1.20  
 $V_H$  = value of waiting time in \$/hr = \$3.00  
 $V_W$  = value of walking time in \$/hr = \$3.00  
 $T$  = value of a transfer = \$.15  
 $K$  = scale of total system (miles of single track) = 150 mi.  
 $F$  = hourly fixed costs if the one-way route/ = \$92  
 $AVC$  = average variable rail costs/veh-mi = \$.913  
 ≈ linearized marginal costs at proposed full service levels of the BART system

### Non-Marginal Cost Pricing

The pricing regime which BART follows in its fare policy is not related in any direct fashion to the agency costs developed above. Thus the user perception of costs differs from the social perceptions. Total perceived costs are then the fare for the particular trip being taken plus the user's valuation of the components of his participation. Substituting the fare for the average fixed and variable components of agency costs, average perceived costs become

$$\frac{\bar{c}'}{Q} = (\text{fare/mi})(L) + \sqrt{\frac{2M \cdot AVC \cdot V_H \cdot P}{Q}} + \frac{L v_v}{V} + W + T \quad ,$$

(assuming that trains are dispatched according to the social optimization described previously). This average perception of costs is roughly the operative pricing regime under practical policy constraints, and in the subsequent work, the implications of both of these pricing options will be explored.

CHAPTER SIX  
COSTS OF COLLECTION AND DISTRIBUTION

The modes of urban transportation being considered in this study are trips by

- integrated auto (collection and distribution performed by the line-haul vehicle)
- integrated conventional bus (primary collection and distribution performed by a vehicle which traverses arterial streets during line-haul)
- integrated busway (primary collection and distribution performed on local and arterial streets by the same vehicle that performs the line-haul on an exclusive roadway)
- rail transit (with collection and distribution performed by other modes)

Each of these modes differs in the costs and characteristics of collection and distribution of patrons. It is the purpose of this chapter to discuss these differences among the modes and integrate these costs with the previous modal costs in a fashion that preserves the simple network emphasis of this study. A complete modelling of the collection and distribution aspects of urban transportation would by necessity take into account the true distribution of the population on the urban plain, finely disaggregated origin and destination data and present a continuous rendering of collection and distribution costs, and, indeed, total trip costs; such a fine-grained analysis does not appear to this writer to be at all feasible in the context of available data, techniques, or analytical costs.

Table 16

Functional Form for an Integrated Trip by Automobile

$$\text{Total costs} = [(O_A + O_n) \left(\frac{L+r}{\ell}\right) + \frac{v_v r}{V} + \frac{G}{\ell} + v_v L t_o] Q + v_v L k \left(\frac{Q^{b-1}}{(sc\ell)^b}\right)$$

where

Q = patrons per hour

$O_A$  = agency operating costs; in \$/veh-mi

$O_n$  = user operating costs; in \$/veh-mi

L = length of line-haul trip; in miles

r = length of access trip; in miles

$\ell$  = average vehicle load; patrons per vehicle

s = number of lanes (one-way) on the facility

V = access speed of autos; in miles per hour

G = parking; in \$ per vehicle per one-way trip

$t_o = .018$	}	parameters of speed/flow relationship
$k = .007$		
$m = 3$		

$v_v$  = value of in-vehicle time; in \$ per hour

c = lane capacity in auto-equivalents per hour

Table 17

Functional Form for an Integrated Trip by Rapid Rail Transit

$$\text{Total costs} = (2MAPv_HQ)^{1/2} + 3(v_Hc\pi r^2A_CQ^2)^{1/3} + \left(\frac{L}{V} + \frac{r}{V_F}\right)Qv_V$$

where

Q = patrons per hour

V = average line-haul (rail) speed; in miles per hour

A = rail agency operating costs; \$ per vehicle mile

A<sub>C</sub> = bus agency operating costs; \$ per vehicle mile

L = length of line-haul portion of trip; in miles

r = average access distance; in miles

M = rail route length; in miles

P = number of cars per train

v<sub>H</sub> = value of waiting time; in \$ per hour

c = cost of secondary access = v<sub>H</sub>/3 mph; in \$ per mile

v<sub>V</sub> = value of in-vehicle time; in \$ per hour

V<sub>F</sub> = average feeder bus speed; in miles per hour

Table 18

Functional Form for an Integrated Trip by Transit Bus

$$\text{Total costs} = 3 \left[ \frac{v_H c \pi r M A_C}{2} \right]^{1/3} Q^{2/3} + \frac{L v_V}{V} Q$$

where

Q = patrons per hour

V = average speed over entire trip; in miles per hour

A<sub>C</sub> = agency operating costs; \$ per vehicle mile

$$= (1.75)(1.08)w^{1.14}P_B^{.0684}V^{-.853}$$

[w = operators' base wage; in \$/hour

P<sub>B</sub> = price of a new bus]

L = length of entire trip; in miles

M = route length; in miles

r = average access distance; in miles

c = cost of secondary access =  $\frac{v_H}{3}$ ; in \$ per mile

π = 3.1416

v<sub>V</sub> = value of in-vehicle time; in \$ per hour

v<sub>H</sub> = value of waiting and walking time

Occom's Law of Parsimony would seem operative here; attempts to develop models of the variety of the real world circumstances in such an analytical environment rapidly tend to become artificial exercises and the additional insight gained by complex modelling of simple assumptions is suspect. Occom's razor has been used throughout this study in an effort to expose the essence of some modern transportation planning problems though not, perhaps, the quintessence. It will be applied during this portion of the analysis as well; the fundamental simplification made here being that average costs in these categories are assumed to apply to all travellers.

The stylized representation of a trip within the transportation networks being considered in this study is diagrammed below in Figure 5. Trips by each mode are assumed to consist of a line-haul portion, A, primary collection and distribution, C and D, and secondary collection and distribution,  $C_S$  and  $D_S$ . For the automobile mode, it is assumed that the vehicle provides primary and secondary collection, line-haul and primary distribution. That is, the integrated auto trip is represented by segments  $C_S$ , C, A and D.  $D_S$ , the secondary distribution would be provided by other modes, in a manner discussed below.

For an integrated bus trip, a single vehicle is used for primary collection, line-haul, and secondary distribution. The trip by this mode thus consists of segments C, A and D. The secondary collection and distribution are provided by other modes. This representation of an integrated bus trip is assumed to apply to both conventional and busway-type bus service, the difference between these types of service being the higher average speeds

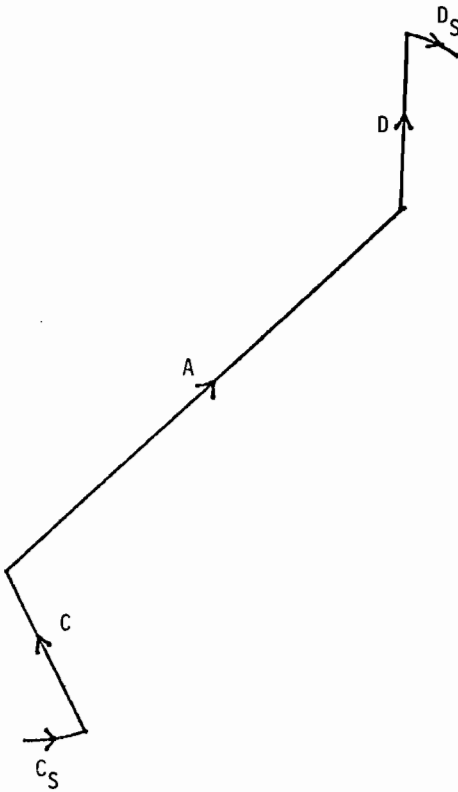


Figure 5: Stylized Integrated Trip



attainable by the busway service.

For the rail transit trip, only the line-haul portion, A, is performed by the rail mode itself. Primary and secondary collection and distribution of patrons are performed by other modes.

Thus the various modes differ in their characteristic of service on the segments of a trip. The length of the line-haul and distribution portions of the trips are assumed to be the same for all of the modes under consideration in this study, but the average collection distance on some routes is greater in the case of rail transit, reflecting the relatively low density of rail transit lines. The specific parameter assumptions of the network analysis performed in this study are presented in the next chapter. This chapter discusses the models of collection and distribution used in this study.

#### Automobile Collection and Distribution Costs

The cost functions developed in Chapter 3 related the generalized costs of trip-making to the intensity of use of the facility. The in-vehicle time required to traverse a given stretch of road was strongly dependent upon the loading of the facility. The collection and distribution segments of an integrated automobile trip are assumed to occur on local and arterial streets, where stop-lights, intersections, roadside obstacles and speed constraints dominate the free-flow characteristics of the facility in determining the relationship between speed and flow. The effect of these constraints is to "flatten" the speed flow relationship and reduce speed's dependence on flow. From the sketchy data available, the marginal influences of an additional vehicle on the speed capabilities

of the stream on even an unsignalled road is smaller by a factor of 3 to 7 than on a highway.<sup>1</sup> The influence on travel times of additional facility loading is thus very small over a fairly wide range of total load. It is assumed then that local street collection and distribution costs are independent of total trip-making, and will become simple additions to the average and marginal line-haul costs developed previously.<sup>2</sup> Using the notation of Chapter 3, the generalized (average or marginal) cost of collection or distribution ( $C_D$ ) over a distance  $r$ , becomes

$$C_D = \frac{r \cdot [O_A + O_n]}{l} + \frac{r}{V_D} \cdot v_v$$

where  $V_D$  is the (constant) average speed of the vehicle in local traffic. The first term on the right hand side is the average generalized operating cost per patron and the second term is the average time cost per patron.

In addition to these costs, there are the costs at the distribution end consisting of parking charges and the user costs of getting to the ultimate destination. As later discussion details, the secondary user costs of distribution will not be assessed for any of the modes. The remaining costs to be estimated for the auto user, then, are the one-way parking costs.

Using an update of Meyer, Kain and Wohl's data on the costs of providing spaces for automobiles, Keeler and Small have presented

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<sup>1</sup>The Highway Capacity Manual [69].

<sup>2</sup>This assumption will make auto trip costs somewhat cheaper than they should be. It will also favor rail transit because the concentrated feeder and distribution patterns of this mode will affect local road conditions more than a bus mode.

data on these costs are various locations in an urban area. The costs differ among locations because of differing opportunity costs of the land. Using their estimates and inflating them to 1973 dollars, the daily and hourly parking costs are derived and presented in Table 19.

Table 19

Daily and Hourly Parking Costs per Space, 1973

<u>Facility</u>	<u>Cost per day</u> <sup>1</sup>	<u>Cost per hour</u> <sup>2</sup>
Fringe lot	\$ .86	\$.10
Low CBD lot	1.65	.21
Low CBD garage	2.51	.31
Med CBD garage	3.01	.38
High CBD garage	3.78	.47

Source: Meyer, Kain and Wohl, p. 212, and Keeler, Cluff, and Small, "On the Average Costs of Automobile Travel in the Bay Area," p. 12-13.

<sup>1</sup>Assumes a 6% interest rate and 255 working days annually.

<sup>2</sup>Assumes an average by-the-hour utilization of 8 hours per space. This seems, in practice, to roughly equate the hourly and daily charges of existing lots and garages, although there is a practice in the Bay Area of charging more per hour for the first hour than for additional hours.

The parking charge assessable to a trip depends on the ultimate destination and the average duration of parking. For a commute trip, it is assumed that average (and marginal) parking charges are for a day at a low density CBD garage or roughly \$.75 per one-way trip, using the data in Table 19.

These charges together with the line-haul costs and feeder

and distribution costs will be assumed to summarize the generalized costs of the auto mode.

### Integrated Bus

The generalized cost function for the integrated bus model presented above includes typical costs of collection in the off-line-haul components of that model. It does not explicitly model the distribution portion of the trip which may include walking from a stop to the destination or transferring to another bus. These costs cannot be built into that model in a complete fashion without knowing more precisely the correlation between origins and destinations. A simpler assumption will be made here, namely that the primary costs of distribution can be built into that model by lengthening the off-line haul portion of total trip length. Generally destinations are much more spatially concentrated than origins for both conventional bus and the busway service envisioned in this study. There is, therefore, less of an off-line haul distribution routing problem than in the collection phase and it is likely that the primary vehicle can serve this function easily. There are still secondary distribution costs of final access from the bus stop to the destination. There does not appear to be any significant difference among the modal alternatives being considered, however, and none of the comparisons performed in this study will be affected by their exclusion. The generalized cost function for integrated bus service is assumed to be that described in Chapter 4 .

### Rail Transit Collection and Distribution

The rail transit mode has limited potential for supplying integrated service to trip-makers. Except for those patrons whose origins and destinations coincide with system termini, the use of the rail transit mode in the line-haul requires the use of other modes in the off-line haul. The relatively low density of system lines and termini raises the average user access costs considerably over that of the other modes being considered.

The mode of access to the rail line is, obviously, a partial determinant of the costs of access to the system and the generalized costs of the mode. Depending upon the distance to the termini and individual circumstances, the rail transit user may choose to walk, take a feeder bus, drive and park, be driven by someone else ("kiss and ride") or take a taxi. Users at different distances might find one mode to be less costly than another in a generalized cost sense. Walking, for example, is less costly at short distances because there are no "fixed" or threshold costs to be overcome (headways, parking charges, etc.), but it is expensive on a per-mile basis because of the slow speed (3 miles per hour) of the average walker and the high valuation of time in this use.

Park-and-ride has the threshold costs of parking charges and the necessity to leave the vehicle at the station for the entire day. It also has relatively high per-mile costs because of slow, local street travel and high operating costs.

The costs of "kiss-and-ride" access are difficult to quantify in a generalized cost fashion because the services of the driver are difficult to evaluate, and the costs depend strongly on the

subsequent use of the vehicles; if the stop at the station is part of a trip that would be made otherwise, the incremental cost in driver's time and vehicle operating costs may be small.

Feeder bus access involves the user in waiting time in addition to that on the rail line as well as the feeder line-haul costs of agency operating costs and in-vehicle time. The relatively slow speed (12 miles per hour) of Bay Area feeder buses involves the trip-maker in an investment of fairly lengthy in-vehicle time. There may also be secondary access costs in walking or driving to the feeder line. An envelope of least-cost feeder alternatives would indicate that an average user would select different modes depending upon the relative level of threshold and distance related costs, as suggested heuristically in Figure 6. The feeder bus mode will be taken here to be the dominant primary access mode; the assumption is made that there is no technical or organizational potential for coordination of feeder bus and rail schedules. Each mode independently optimizes its service. The feeder bus, like the integrated bus service, then, would have generalized total costs of

$$TC = 3 \sqrt[3]{\frac{2V_H C_{\pi} r \cdot r \cdot A_C Q^2}{2}} + \frac{rv_V Q}{V_F}$$

where  $r$  is the length of the average feeder trip, and  $V_F$  is the average feeder bus speed and assuming that the feeder bus route length equals twice the average trip. The total costs of a complete rail transit trip becomes

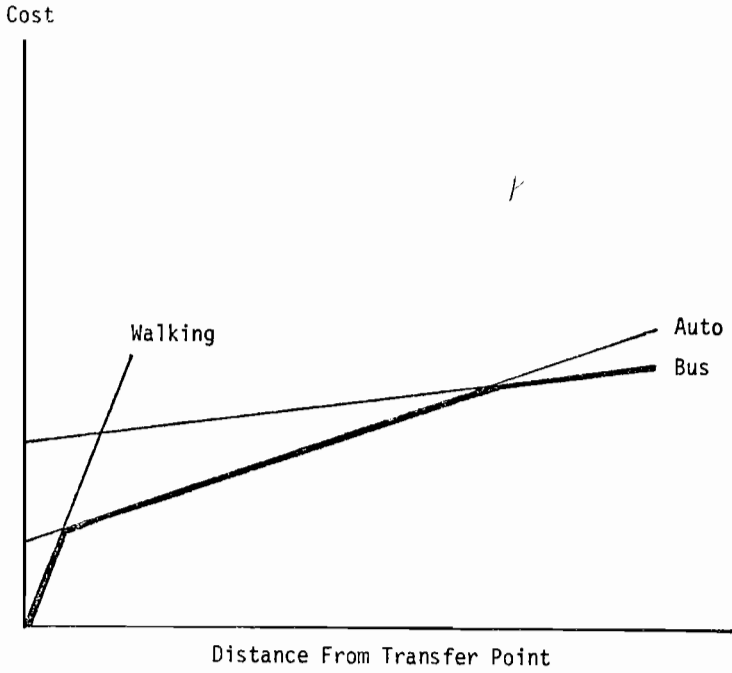


Figure 6: Schematic Access Costs

$$C = \sqrt{2 \cdot MAVc \cdot P \cdot V_H \cdot Q} + \frac{QLv_v}{V} \\ + 3 \sqrt[3]{\frac{2V_H c \pi r^2 A_c Q^2}{2}} + \frac{rv_v Q}{V_F} .$$

It remains to describe the costs of secondary access,  $c$ , as used now in both the rail transit and bus modes.

The problem is analytically similar to that of primary access on the rail mode; there are various modal alternatives which may be more or less feasible at different distances depending upon their service characteristics. However, the secondary access distance,  $c$ , is generally much shorter than the primary access distance and the mode of secondary access is more likely to be walking. The cost per mile,  $c$ , of secondary access can then be written

$$c = \frac{v_w}{V_w} \approx \frac{v_w}{3}$$

where  $v_w$  is the value of walking time in dollars per hour and  $V_w$  is the average walker's speed, roughly 3 miles per hour. This value will be used in all of the integrated trip cost calculations used in subsequent modelling.



## CHAPTER SEVEN

## COMPARISON OF TYPICAL TRANSIT PROJECT ALTERNATIVES IN SIMPLE NETWORKS

Many transit planning problems arise in the context of the decision to provide additional, non-automotive capacity to an existing automotive corridor that is congested during peak period use. In many modern central cities, the alternative of providing additional roadway capacity is constrained by public aesthetic, environmental or land-use considerations, so that this alternative will not be considered a relevant one here. The range of transit alternatives is quite large and the possible technologies include everything from taxis and guideways to exotic airborne vehicles. The list of alternatives for this work, however, has been confined to the exclusive lane bus, conventional arterial bus and a BART-type rail transit technology. Their service characteristics, as outlined in previous chapters, vary in the aspects of speed, accessibility, need to transfer, and the necessity of waiting for the vehicle to arrive. The "generalized cost" methodology developed in this study translated these service characteristics into a single, comparable datum. It remains now to apply this methodology in concrete examples with specified service environments to see if there are consistent, general implications to be drawn with respect to the comparative social costs and benefits of the various modes.

As detailed in the theoretical material above, the scale of the consumer benefit of a transit improvement is related to the net generalized cost savings enjoyed by the users as a result of the service. These net benefits to travellers must then be compared

with capital costs of the rights-of-way, structures, and other fixed costs of operation to determine the economic feasibility of the project.

Under a marginal cost pricing regime, each user would perceive the incremental (generalized) social cost incurred by his use of the system. The equilibrium volume of users on each mode would then be the cost-minimizing one, as shown in Chapter 2 . However, there are practical (and probably rigid) constraints on the pricing methodology that may be employed in a real-world pricing situation. The perceived cost will yield an equilibrium volume of users on each mode that may not be the cost-minimizing one. In general, total social (system) costs incurred under a perceived cost pricing regime will be greater than under a marginal cost pricing regime. The models discussed in this chapter present system cost comparisons assuming both marginal cost pricing and a pricing regime that approximates the existing perception of cost. The auto mode, characterized by increasing marginal costs as volumes increase, tends to be underpriced; perceived costs are substantially less than marginal costs at most levels of usage. The transit modes being analyzed are generally characterized by decreasing marginal costs and are typically overpriced in extant markets for their services.

#### Experiments with Simple Path Models

We are interested in exploring the extent to which one mode or technology is better able to relieve the corridor of its existing congestion in an economically efficient manner than the alternatives. It is likely that the interaction of the different cost

functions produces a ranking of the alternatives that is dependent upon the average length of the trips made, the implicit value that individuals place upon their time, the average distance to the line-haul facility, and the patron load that is anticipated for the corridor. Therefore some simple path models are tested over a range in values of these variables in order to explore the sensitivity of the ranking to these environmental parameters.

The equilibrium patron volumes on the automobile mode and the transit mode being considered are determined by discovering the modal split (i.e. the division of total trip demand among the modes) at which marginal (or perceived) costs are equal in the corridor on both of the modes; if no such central solution exists, the traffic is assigned entirely to the mode with lower costs (the dominant corner solution). As detailed earlier, these Kuhn-Tucker first order conditions are those that describe the solution to a generalized system-cost minimization process; alternatively they may be thought of as the equilibrium conditions of a non-competitive game, in which case they describe a Nash equilibrium where no player (traveller) can improve his circumstances by redirecting his activity (choice of route or mode) [ 70 ]. Considering first the performance of the different modes in the context of a single, simple path, we imagine trip-making in a region to be summarized by demands for travel between two points A and B. There are two directed arcs connecting these points, and these arcs represent the (two) available means of transportation. Each arc is represented by a travel cost function which depends upon the flow experienced by the mode, the length of the route, the value of time to the users, the costs of

access to the line-haul portion of the trip and other parameters. There will exist an equilibrium flow on each mode and a total system (generalized) cost associated with the equilibrium flow.

The cost functions for each mode are the continuous specifications presented in Chapters 3 and 4. In this simple context the network analysis of Chapter 2 reduces to the constrained simultaneous equation system

$$(1) \quad f(x) = g(y)$$

$$(2) \quad x + y = D_{AB}$$

$$(3) \quad x, y \geq 0$$

where  $f(x)$  is the marginal or perceived cost of travel on mode  $f$  as a function of flow  $x$ ,  $g(y)$  is the relevant cost of travel on mode  $g$  as a function of flow  $y$ , and  $D_{AB}$  is the total demand per period for travel between  $A$  and  $B$ . If the automobile represents one of the modes, for example, and an integrated busway the other, and if the pricing regime is marginal cost pricing, (1), (2) and (3) become

$$(1') \quad 2 \left[ \frac{V_H c \pi r M A}{2} \right]^{1/3} x^{-1/3} + \frac{(L+r)v_v}{V} \\ = [0_A + 0_n] \left[ \frac{L+r}{\ell} \right] + \frac{v_v r}{V} + \frac{G}{\ell} + v_v L t_o + (m+1) \frac{v_v L K (y)^m}{\ell^m s c^m}$$

$$(2') \quad x + y = D_{AB}$$

$$(3') \quad x, y \geq 0$$

Since it is generally not possible to solve this system analytically,

various numerical techniques were employed which systematically explored the range of feasible values of  $x$  and  $y$  and sought minimization of the difference between the right-hand side and left-hand side of equation (1).<sup>1</sup> The models for the modes developed earlier were parameterized using cost data that was roughly applicable to the San Francisco Bay Area in 1973 dollars. The basic comparisons explored were:

- 1) Auto with no transit available.
- 2) Auto with conventional integrated bus service available.
- 3) Auto with an integrated exclusive lane bus service operating on its own right of way.
- 4) Auto with an integrated exclusive lane bus service operating on a "condemned" freeway lane<sup>2</sup> (called priority bus service).
- 5) Auto with a rapid rail line haul service fed by conventional feeder buses.

In order to explore the sensitivity of the modal split results with respect to certain important variables, the length of the average line haul trip, the length of the average feeder access, the value of time and the level of path demand were varied during the analysis. In addition, for each parameter set, the two pricing regimes (marginal and perceived cost pricing) were compared. From the modal split (that is, the various equilibrium flows on the competing modes) the total generalized system costs of satisfying the

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<sup>1</sup>These methods were all based largely on SIMEX, a simultaneous equation solving algorithm implemented on the University of California's CDC 6400 [ 71 ].

<sup>2</sup>Thus this alternative involves reducing automotive facility capacity by one lane in each direction.

path demand were calculated for each mode and each set of parameters. In all, over 250 simulations were performed. The equilibrium and total system costs of some of the alternatives appear in Figures 7 through 9 .

It can be seen from a review of these figures that there is a significant gross<sup>1</sup> generalized cost advantage of combined auto and exclusive lane bus transit service over satisfaction of trip demands by rail transit or conventional bus. However, the absolute level of the advantage as well as the ranking of the various alternatives depends strongly on the parameters of the experiment. The substantial economies of scale of the various transit alternatives, if exploitable, make transit relatively more effective at high levels of demand when roadway facilities are fixed, but much less so at low levels of path demand, as can be seen from Figure 7 . It is also apparent from the same figure that the current pricing methodologies (perceived cost pricing) significantly influence the gross system costs; total costs are generally greater than under the marginal cost pricing regime because the pricing encourages over-use of the auto mode and discourages the use of transit where substantial economies of scale wait to be exploited.

Figure 8 displays the influence on system costs and relative modal efficiency of different user time values. It can be seen that the relationship between time value and total costs is similar for the high speed modes, but that as time valuation increases, the

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<sup>1</sup>It should be emphasized that at this point, the fixed capital costs of the transit alternatives have been excluded. They will be analyzed later in the chapter.

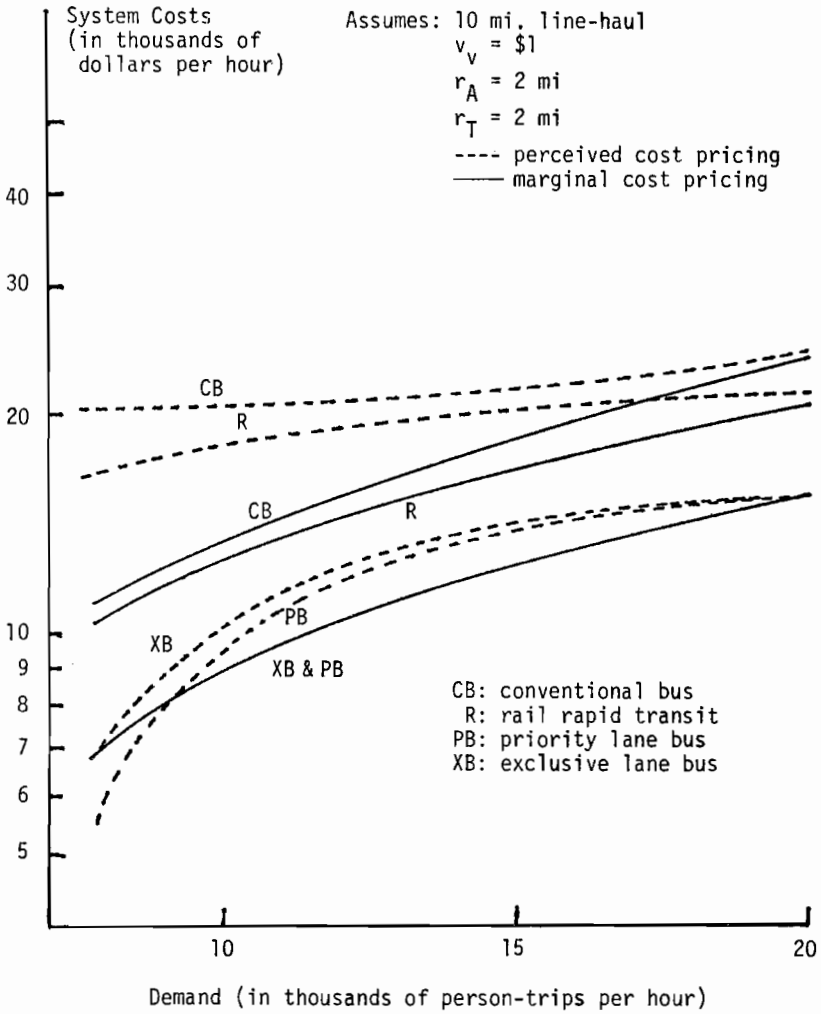


Figure 7: Simple Path System Costs as a Function of Patron Demand

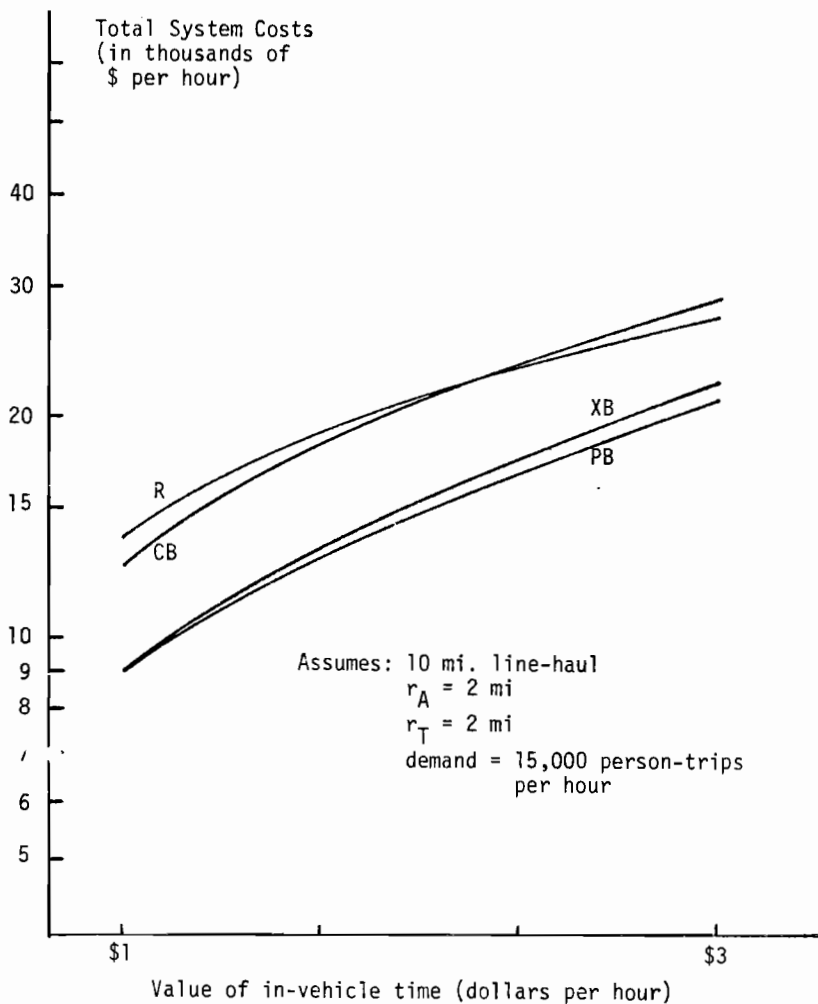


Figure 8: Simple Path System Costs  
 as a Function of the Value  
 of In-vehicle Time



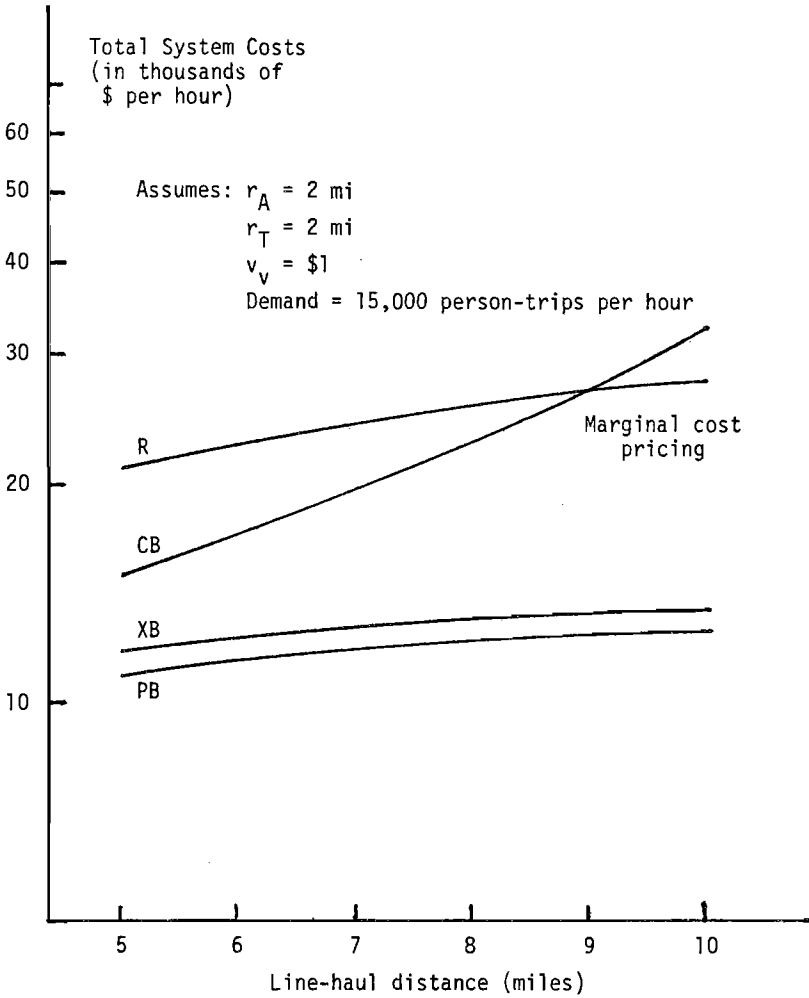


Figure 9: Simple Path System Costs  
as a Function of Line-Haul  
Distance

conventional bus mode becomes relatively more costly. It becomes less competitive with the automobile and as patrons shift to that mode, total system costs rise. A similar effect is noted in Figure 9 where system costs for the various modal alternatives are graphed against line haul distance. The conventional bus alternative (with its inherently lower service speed) experiences a relatively rapidly rising equilibrium system cost as line haul distance increases and the user valuation of in-vehicle time comes to dominate costs.

The analysis of the comparative advantages and disadvantages of the various modes is facilitated if the results of the simulation are generalized in a continuous fashion, rather than in a graphical format. It is useful to develop functions relating modal split and system costs to the values of the major service parameters. This can be accomplished by using the data from the simulations and developing the parameters econometrically. The total number of simulations (parameter combinations) was 60 per mode.

With modal split<sup>1</sup> as the dependent variable, care must be taken in estimating functional relationships because of the limited domain of the modal split values; modal split is a ratio taking on values of 0 to positive infinity. Estimation by ordinary least squares of a relationship of the form

$$MS = \beta_0 + \beta_1 x_1 + \dots + \beta_n x_n + \epsilon$$

(where MS = the modal split and  $x_1, \dots, x_n$  are explanatory variables) would be illegitimate since the systematic part of the right-hand side may be less than 0, whereas MS must be non-negative.

<sup>1</sup>Defined here as equilibrium auto trips ÷ equilibrium transit trips.

A log transformation of the dependent variable brings its values within the range of negative infinity to positive infinity and permits estimation of the relationship as a linear or linear-in-the-logs function of the right-hand side variables. While we suspect from our knowledge about the modal cost functions that the modal split relationship is non-linear, we have no a priori way of determining the advantage of one functional form over another. Therefore the data was used to estimate the coefficients of both of the following forms of the modal split function.

$$(4) \quad \log MS = C + \beta_1 RA + \beta_2 RT + \beta_3 LEN + \beta_4 TVAL + \beta_5 DEM \\ + \beta_6 DUMMY + \epsilon$$

$$(5) \quad \log MS = C + \beta_1 \log RA + \beta_2 \log RT + \beta_3 \log LEN \\ + \beta_4 \log TVAL + \beta_5 \log DEM + \beta_6 DUMMY + \epsilon$$

where

RA = length of auto feeder distance (miles)

RT = length of transit feeder distance (miles)

LEN = length of line-haul portion of the trip (miles)

TVAL = the value of in-vehicle time

DEM = path demand

DUMMY = a dummy which equals 0 if marginal cost pricing is used  
and equals 1 if perceived cost pricing is used

The coefficients of the second form (equation (5)) have the interpretation of being the elasticity of the modal split with respect to the choice variables.

Table 20

## The Modal Split on Simple Paths as a Function of Service Environment

	C	RA	RT	LEN	TVAL	DEM	DUMMY	R <sup>2</sup>	N
A. Linear Formulation									
1. Condemned Lane Bus	-4.63 (2.74)	-1.26 (1.52)	1.33 (.69)	-.124 (.27)	2.05 (.49)	-.000588 (.00012)	6.6 (.99)	.63	60
2. Rapid Rail Transit	-4.29 (2.45)	-1.29 (1.36)	3.19 (.622)	.66 (.249)	2.41 (.440)	-.00061 (.0001)	10.79 (.88)	.82	60
3. Exclusive Lane Bus	-8.21 (2.69)	-.15 (1.48)	.622 (.68)	-.057 (.27)	3.14 (.48)	-.00048 (.00012)	9.40 (.96)	.74	60
4. Conventional Bus	-7.19 (2.72)	-2.05 (1.50)	.98 (.69)	.64 (.27)	3.71 (.49)	-.00055 (-.00012)	9.22 (.97)	.77	60
B. Log Formulation									
1. Condemned Lane Bus	72.5 (16.4)	-1.93 (2.02)	4.08 (1.53)	-1.97 (2.02)	3.73 (.87)	-8.57 (1.67)	6.63 (.95)	.66	60
2. Rapid Rail Transit	85.8 (14.9)	-.97 (1.84)	7.40 (1.39)	-6.2 (1.84)	4.37 (.79)	-8.92 (1.51)	10.79 (.86)	.83	60
3. Exclusive Lane Bus	58.8 (16.4)	-.64 (2.02)	2.62 (1.53)	-1.27 (2.02)	5.7 (.86)	-6.8 (1.67)	9.39 (.95)	.75	60
4. Conventional Bus	60.9 (16.4)	-3.08 (2.03)	3.07 (1.53)	3.81 (2.03)	6.76 (.87)	-8.06 (1.67)	9.22 (.95)	.78	60

Table 20 (continued)

Note: The dependent variable in both formulations is the natural log of the modal split (auto travel ÷ transit travel).

C = constant term  
 RA = length of auto feeder in miles  
 RT = length of transit feeder in miles  
 LEN = length of line haul trip in miles  
 TVAL = value of in-vehicle time in dollars per hour  
 DEM = path demand in patrons per hour  
 DUMMY = 0 if marginal cost pricing was used  
           = 1 if perceived cost pricing was used

The numbers in parentheses represent standard errors of the estimated coefficients.

The formulations in equations (4) and (5) were estimated for each of the binary modal alternatives. These estimated relationships are reproduced in Table 20. There does not appear to be any clear statistical reason for accepting one hypothesized functional form over the other (nor do there appear to be any substantial differences in the analytical interpretation of the results); the log form has the advantage, however, of convenient interpretation of the coefficients, and the discussion revolves around the coefficients of this model. While the modal split per se is not necessarily an indication of the economic feasibility of a transit alternative, it is an important measure of the success of a modal combination in attracting users away from the (expensive) automotive alternative, and an analysis of the comparative susceptibility of the modes to the service variables is warranted. It should be emphasized however that the coefficients may not be relevant over a wider range of values than those used in the simulation.

As the signs of the estimated coefficients in Table 20 indicate,<sup>1</sup> transit usage is favored (ceteris paribus) by increases in RA, LEN, and DEM. That is, the following generalizations about the influence of these environmental variables may be made:

1. As the length of the auto access, RA, increases relative to transit, more users will shift to transit use. Note that while the sign of the coefficient of RA is consistently negative for both formulations, the statistical significance of the coefficients is low and the magnitude of the elasticity of modal split with respect to this variable is small. As a policy variable, then,

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<sup>1</sup>Note that a negative coefficient implies an elasticity with respect to modal split in favor of transit, and a positive sign implies a tendency of increases in that variable to favor automotive travel.

the difficulty of automotive access to the line-haul facility is only a mild influence on the tendency to shift to transit usage, at least within the range of variations of this variable in the simulation. Note, however, that the sensitivity of the modal split to the length of transit access,  $RT$ , is much greater and more significant statistically. The tendency for users to shift to transit usage from automobile use is several times more sensitive to a decrease in transit access than it is to an increase in auto access. The log formulation implies that, for example, the elasticity of the modal split in the condemned bus lane alternative with respect to an increase in auto access is less than half of that which would be observed following a proportionate decrease in transit access distance.

2. As the average length of the line-haul portion of the trip increases, users will tend to increase their use of certain forms of transit. This effect, while not significant statistically for any of the modes except for rail transit, seems to favor those modes with the largest relative speed advantage over the automobile. Thus the conventional bus (which operates at line-haul speeds of about twenty miles per hour) actually loses patrons to the automobile (ceteris paribus) as the line-haul distance increases. The exclusive lane bus offers line-haul speed advantages over the automobile in a similar environment and thus (in the log formulation) the modal split responds with greater than unitary elasticity to an increase in the line haul trip length. The priority lane bus increases the relative speed of the bus service (due to increased congestion on the auto mode as a result of the decrease in freeway

capacity); the elasticity of the tendency for transit to be favored over automobile (if the estimates are to be believed) is greater than that of the exclusive right-of-way version. The rail transit alternative is strongly and significantly favored in serving trips of long average line-haul length because of its high average line-haul speed.

3. As the path demand, DEM, increases, the economies of scale which the transit modes display combined with the rapidly increasing potential for congestion on the automobile facilities diametrically influence the comparative advantage of transit and auto travel. This effect is very large and significant. The elasticity of modal split with respect to this environmental characteristic (in the logarithmic version of the modal split function) varies from 6.8 to 8.9. This is an analytical demonstration of the commonly observed viability of transit service in densely travelled corridors. As the number of potential patrons increases, the transit agency can offer more frequent service and more densely placed routes, substantially reducing the comparative attractiveness of the automobile.

There are several environmental variables in addition to transit access distance which, if large or growing, tend to favor automotive travel. In the modal split functions of Table 20, these can be identified as those coefficients with positive signs, TVAL and DUMMY. These statistical results have the following interpretation:

1. The value of time perceived by users is a significant influence on the mode selected by travellers and, in general, users with high values of time will tend to prefer the auto over any of



the forms of transit. The effect of high time values on modal split is, of course, strongest on the slowest of the transit modes, the conventional bus technology and weakest on the mode that combines high line haul speeds and reduced capacity on the automobile facilities, the priority lane bus. The significance of time value in the mode choice decision forbodes difficulties for transit in the future as the opportunity costs of time increase unless total travel demand increases rapidly as well.

2. The bias against transit usage of perceived cost pricing regimes is apparent in the dimension and significance of the coefficient of the binary variable DUMMY (which takes on a value of zero if marginal cost pricing was in effect in the path simulation and a value of one otherwise). The magnitude of this effect derives from the fact that perceived cost pricing in the auto mode underprices its services while existing pricing regimes in the transit industry overprice those modes relative to their marginal social costs. Existing pricing methodologies, because of their accounting rather than economic emphasis, create a two-edged prejudice against transit use in contemporary urban transportation markets.

Modal split, as was emphasized above, does not imply economic feasibility of any proposed alternative to freeway congestion. We are ultimately interested in the system cost advantages of one mode over another; we want to minimize the social burden of carrying the given demand for trips between the various origins and destinations in the region. For a set of specific environmental parameters, the data reveal the relative social cost of providing a given level of trips by the various

modal combinations.

In order to express the relationship between the environmental parameters of interest and the system costs in a continuous fashion, econometric models similar to those developed in the modal split analysis will be employed. The relationship between system cost and the independent variables of auto access distance, transit access distance, line-haul distances, time value, path demand and a pricing regime dummy was tested in a linear and log-linear formulation as in equations (6) and (7) respectively:

$$(6) \quad \text{COST} = C + \beta_1 \text{RA} + \beta_2 \text{RT} + \beta_3 \text{LEN} + \beta_4 \text{TVAL} + \beta_5 \text{DEM} \\ + \beta_6 \text{DUMMY}$$

$$(7) \quad \log \text{COST} = C + \beta_1 \log \text{RA} + \beta_2 \log \text{RT} + \beta_3 \log \text{LEN} \\ + \beta_4 \log \text{TVAL} + \beta_5 \log \text{DEM} + \beta_6 \text{DUMMY}$$

where

COST = total system (generalized) costs in thousands of dollars per hour

RA = average auto access distance in miles

RT = average transit access distance in miles

LEN = average length of the line-haul portion of the trip in miles

TVAL = value of in-vehicle time in dollars per hour

DEM = path demand in patrons per hour

DUMMY = 0 if marginal cost pricing was employed in the simulation

= 1 if perceived cost pricing was employed

The results of estimating the coefficients of equations (6) and (7) from the simulated path data are presented in Table 21. The log-linear formulation appears to be slightly more effective at explaining the variance in the observed relationship and, again, its coefficients may be conveniently interpreted as the elasticity of system cost with respect to the choice variables. The log-linear relationships themselves might be thought of as reduced form system cost functions based on a Cobb-Douglas type production relationship involving the mix of two technologies. The constant term and the coefficients for RA, RT and LEN may be thought of as part of the efficiency term in the standard Cobb-Douglas formulation.

The interaction of a mode characterized by decreasing returns to density (the automobile) and various transit alternatives characterized by generally increasing returns to density produces interesting outcomes in the cost simulation. It is apparently possible, under some circumstances, to increase the generalized cost of the auto mode and reduce the total cost of serving the demand system-wide. The coefficients on RA, the auto access distance, for example, are consistently negative (although weak and of low statistical significance) implying that an increase in auto access distance tends to decrease overall system costs. This is to be expected as a result of the fact that as the relative cost of the automobile increases and patrons switch to transit, the increased loading of the transit system lowers the average cost of its services by more than the (remaining) auto users' average costs have risen as a result of the increase in access distances.

Some of the differences among the cost elasticities with respect

Table 21

## Gross Path Cost as a Function of Service Environment

	C	RA	RT	LEN	TVAL	DEM	DUMMY	R <sup>2</sup>	N
A. Linear Formulation									
1. Condemned Lane Bus	-28.5 (3.21)	-1.26 (1.77)	3.52 (.82)	1.07 (.33)	9.45 (.58)	.00097 (.00014)	3.16 (1.15)	.88	60
2. Rapid Rail Transit	-51.8 (6.37)	-.64 (3.53)	4.94 (1.62)	1.59 (.65)	10.55 (1.14)	.0022 (.00028)	8.23 (2.29)	.79	60
3. Exclusive Lane Bus	-42.7 (6.77)	-3.17 (3.75)	1.45 (1.72)	1.39 (.69)	10.87 (1.22)	.00144 (.0003)	6.44 (2.43)	.71	60
4. Conventional Bus	-60.0 (6.85)	-1.09 (3.79)	1.78 (1.73)	2.98 (.70)	11.52 (1.23)	.0025 (.0003)	7.24 (2.46)	.79	60
B. Log Formulation									
1. Condemned Lane Bus	-5.14 (.467)	-.0799 (.057)	.438 (.044)	.338 (.057)	.865 (.025)	.680 (.048)	.127 (.027)	.97	60
2. Rapid Rail Transit	-7.78 (.79)	-.017 (.097)	.378 (.074)	.383 (.097)	.655 (.042)	.991 (.080)	.249 (.046)	.91	60
3. Exclusive Lane Bus	-6.53 (.732)	-.00177 (.090)	.377 (.068)	.384 (.090)	.891 (.039)	.817 (.075)	.194 (.042)	.94	60
4. Conventional Bus	-9.25 (.74)	-.0618 (.091)	.195 (.069)	.721 (.091)	.692 (.039)	1.09 (.075)	.197 (.043)	.93	60

Note: The dependent variable in the linear formulation is the system cost of the equilibrium auto and transit traffic. In the log formulation, it is the log of system costs. Cost is in thousands of dollars per hour.

to output can be explained by this interaction as well. It can be seen from the coefficient of DEM (path demand or system output) that there are at least slight economies of density in the combined technologies of auto and the transit alternatives being considered here. The coefficient is statistically indistinguishable from 1.0<sup>1</sup> for the rail transit and conventional bus alternatives (implying constant returns), but this is in comparison with the exponentially increasing costs of travel on the fixed roadway with no transit alternative. The cost functions of all of the transit alternatives being considered display substantial relaxation of the decreasing returns to traffic density that characterize the auto mode; ceteris paribus the smaller the coefficient of the output variable, DEM, the more effective is the mode in enabling its economies of density to be exploited in competition with the automobile. In this respect, the priority lane version of the exclusive lane bus technology is most effective followed by the exclusive right-of-way version of this technology, then the fixed rail alternative followed closely by the conventional bus technology. This ranking corresponds to the ranking in terms of absolute cost of the alternatives in most of the simulations reported in Table 21. One might a priori expect the condemned lane version of the exclusive lane bus to be costly because of the additional congestion caused the auto traffic by the reduction in roadway capacity. However, it is apparent from these simple simulations that the substantial scale economies that exist in the integrated bus service in reduced waiting and walking time, combined with the relatively high line-haul

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<sup>1</sup>At the 1% level.

speeds of the technology, offset much of the increase in congestion and travel costs experienced by continuing auto users, at least within the range of service environment parameters employed in the simulation. Because the change in relative prices is a result of both an increase in the relative price of auto travel and a decrease in unit transit travel costs (because of heavier loading of the system), there is a two-fold effect on system costs: costly auto use is curtailed and the increased density of transit usage enables further exploitation of the inherent scale economies of the mode.

Because costs on the automobile facility do not increase as rapidly as demand grows for the other alternatives being considered, the decrease in auto-related costs as users switch to transit is not as profound and the elasticity of system costs to the increase in demand on the path is greater. The conventional bus technology and rapid rail transit offer the least cost-saving alternative to the automobile; hence, system costs respond most elastically to switch-overs to these modes.

The cost function coefficients reveal the expected sensitivity of the conventional bus alternative to long line-haul trip lengths. The service speed of the other three modes is comparable; hence their cost functions display similar cost elasticities with respect to this variable. The slower service speed of the conventional bus impairs its cost competitiveness in an environment of trips requiring long average line-hauls. More patrons will continue to use the auto mode and, hence, response of costs to lengthening trip-length is greater.

Similarly, the coefficients of the value of time, TVAL, reflect

the effectiveness of the various transit modes in attracting time-valuing users away from the automobile. As the modal split analysis showed, high values of time favor auto use; hence, these alternatives with low elasticity of cost tend to offer a less attractive trade-off of time and other costs to the user. With an increase in the value of time, since fewer users are patronizing the time consuming transit mode, costs rise less quickly than for those transit modes that have attracted a greater proportion of users away from the automobile (namely, the two versions of the exclusive lane bus services).

#### Experiments with Network Models

The simulations performed comparing the performance of the various transit alternatives in the context of simple paths are useful in general ways in describing the relative advantages and liabilities of the various transit modes. Most realistic project alternatives, however, involve networks of paths and demands for travel among various origins and destinations. While it is likely that the ranking of alternatives discovered in the path analysis will generally be relevant for networks as well, the complexity of the traffic interaction in a network environment may subject the analysis to a more rigorous test. Moreover, the network analysis will enable us to make some rough judgments as to the relative economic feasibility of an actual transit investment, the BART rapid rail system,<sup>1</sup> in a more realistic (though still highly

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<sup>1</sup>The system is described in detail in Chapter 6 .

stylized<sup>2</sup>) data environment.

The peak hour travel patterns in the portion of the Bay Area served by BART are modelled using a 16 link, 5 node, 20 demand pair network as depicted in Figure 10. 8 of the links are unidirectional transit links, and 8 others are unidirectional freeway links.

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<sup>1</sup>There is no theoretical constraint on the detail in which the network can be described. There are practical computational limits, however, because the network flow-solving algorithms rapidly become more expensive as the size of the network increases. The author preferred to devote limited computational resources to a more thorough exploration of the behavior of a simpler network, where descriptive parameters could be easily modified, than to attempt to develop more complicated and tentative versions.



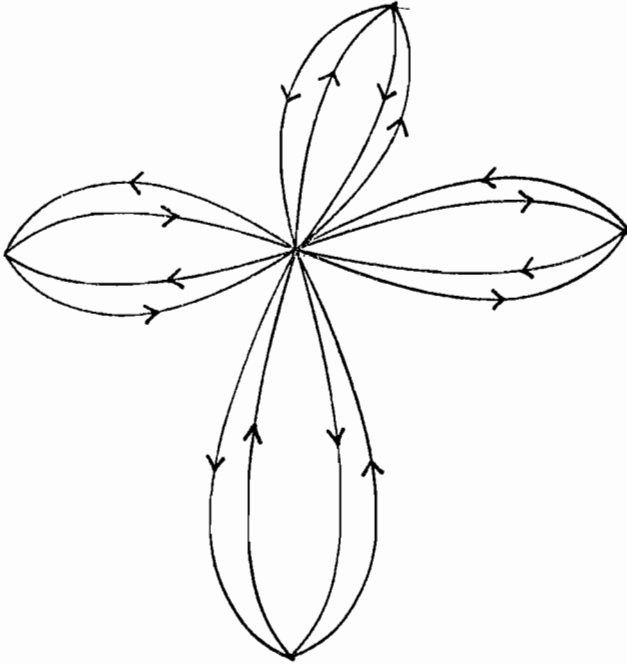


Figure 10: Simplified Network of BART Travel Patterns

Each link is described by a cost function relating the generalized user costs to the flow on the paths in which the link is a component.<sup>1</sup> The network was parameterized over a range of time values for each of five modal mixtures.

- 1) auto with no transit available
- 2) auto competing with conventional integrated bus service
- 3) auto competing with exclusive lane bus service operating on its own right of way
- 4) auto with priority lane bus service operating on a "condemned" freeway lane.<sup>2</sup>

Each path's cost functions were modelled in the manner described in the chapters on modal costs with the generalized costs of a complete path consisting of the total of access, line-haul, waiting costs, etc., described previously. With a simple network structure such as is used here, the underlying assumption is that all demand originates and arrives at single points in the plane rather than the multitude of origin and destination pairs that obviously characterize the real world. The environmental parameters characterizing each node and link are given in Table 22 along with a description of the Bay Area locations and corridors, for which they are rough surrogates.

The origin-destination data was drawn from workplace data contained in the 1970 census, aggregated to correspond to the interurban

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<sup>1</sup>See Chapter 2 for a mathematical presentation of this relationship. With 20 origin-destination pairs each one-way auto link is potentially involved in a maximum of 7 paths (4 pure auto paths, 3 auto-to-transit paths). Each transit link is potentially involved in only 4 paths, since transit-to-auto transfers are disallowed.

<sup>2</sup> This involves reducing freeway capacity by one line in each direction.

Table 22

## Service Parameters of Network Model

Link Number	Line-Haul Length	Length of Access	One-Way Freeway Lanes	Bay Area Corridor Modelled
(Auto Links)				
1	10 miles	2 miles	5	San Francisco <sup>1</sup> -Oakland
2	10	2	5	Oakland-San Francisco
3	5	2	4	North Alameda County <sup>2</sup> -Oakland
4	5	2	4	Oakland-North Alameda County
5	10	1	8	South Alameda County-Oakland
6	10	1	8	Oakland-South Alameda County
7	10	2	4	N.E. Contra Costa County-Oakland
8	10	2	4	Oakland-N.E. Contra Costa County
(Transit Links)				
9	10	2	-	San Francisco-Oakland
10	10	2	-	Oakland-San Francisco
11	5	2	-	North Alameda County-Oakland
12	5	2	-	Oakland-North Alameda County
13	10	2	-	South Alameda County-Oakland
14	10	2	-	Oakland-South Alameda County
15	10	2	-	N.E. Contra Costa County-Oakland
16	10	2	-	Oakland-N.E. Contra Costa County

## Assumed Service Speeds

Exclusive R-O-W bus: 40 mph

Priority bus: 40 mph

Conventional express bus: 20 mph

Feeder bus: 12 mph

Rail transit line-haul: 40 mph

<sup>1</sup>This includes trips originating west of San Francisco.<sup>2</sup>This includes trips originating in the north-west portion of Contra Costa County as well.

flows used in the network and reduced to hourly patron volumes.<sup>1</sup> The origin-destination matrix (rounded to the nearest thousand patrons) that was used in the simulations appears in Table 23.

The network traffic allocation problem was then written as a non-linear program as detailed in Chapter 2 and a computer program utilizing the Frank-Wolfe algorithm was employed to determine equilibrium (cost-minimizing) flows. Because the unit cost functions on the transit links are generally decreasing functions of flow, the objective function is not pseudo-convex, a condition required for the existence of a unique solution to the programming problem [ 72 ]. Therefore the transit cost functions were approximated by a series of constant-cost functions in a two-stage iterative sequence<sup>2</sup>:

1) The unit transit costs were assumed to be those that applied when one-half of the maximum patron demand on the link was directed to transit. For the link loads experienced in this network, unit transit costs were essentially linear at this level of usage. The equilibrium flows on the network were then calculated using these cost functions on the transit links.

2) If the equilibrium transit flows were substantially less than one-half the maximum patron demand, the link costs were recalculated using as the corrected estimate of equilibrium transit link costs the unit cost of carrying the equilibrium flow. Upon recalculation of equilibrium flows, it was found in all but a few cases

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<sup>1</sup>A three-hour peak period is assumed with equal distribution of volumes among those three hours.

<sup>2</sup>As an inspection of the graphs of the various modal cost functions in previous chapters reveals, the unit cost functions are nearly linear at high flow volumes, so the error introduced by this process is probably moderate.

Table 23

Network Patron Demand per Peak Hour

<u>Origin Node:</u>	1	2	3	4	5
<u>Destination Node</u>					
1	---	20,000	20,000	15,000	25,000
2	1,500	---	30,000	5,000	15,000
3	50,000	20,000	---	20,000	30,000
4	1000	30,000	5,000	---	1,500
5	1000	10,000	25,000	5,000	---

that the transit link was eliminated from the solution set. If it was not eliminated, however, a second set of equilibrium transit costs was calculated and the process repeated.

The performance of the Frank-Wolfe algorithm was very satisfactory, though not inexpensive. Convergence (at 5% accuracy) was generally achieved in 15 decimal seconds or less; thus each trial of the network flow model cost roughly \$1.80. The two-stage process described above weakened the results only when the auto-use/transit-use ratio of the network was very high and tends, if anything, to favor transit use slightly because transit costs were not readjusted (raised) more than twice because of the expense of recalculating equilibrium flows.

The modal splits<sup>1</sup> and system costs for the various versions of the network experiments appear in Tables 24 and 25. Because we are interested in the future benefit stream as well, the model was also run using demand data likely to exist in 1990. The demands were derived from the actual 1970 demand data by applying a factor equal to the rate of growth of population in the area anticipated by the Division of Bay Toll Crossings [ 73 ]. It was originally anticipated that the relative rates of growth of the cost components of the transit cost functions would influence modal priorities as time passed. However, a closer review of the historical experience of the relevant price indices weakened this presumption considerably. Table 26 presents the compound rates of growth of various input prices. The dollar valuation of user's time is probably most closely

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<sup>1</sup>Again defined as the ratio of auto users per hour to transit users per hour.

Table 24

Modal Splits in the Network Model

Value of in-vehicle time:	1973			1990		
	\$1	\$3	\$5	\$1	\$3	\$5
<u>Marginal cost pricing</u>						
Auto vs. conventional bus	0.	.95	4.07	0.	.70	2.41
Auto vs. exclusive R-0-W bus	0.	0.	.78	0.	0.	.55
Auto vs. priority bus	0.	0.	.36	0.	0.	.33
Auto vs. rapid rail	0.	.67	1.97	0.	.35	.78
<u>Perceived cost pricing</u>						
Auto vs. conventional bus	.35	8.2	35.2	.19	2.80	9.6
Auto vs. exclusive R-0-W bus	0.	2.1	7.1	0.	1.49	4.21
Auto vs. priority bus	0.	.75	1.7	0.	.69	1.76
Auto vs. rapid rail	.82	6.7	17.6	.48	2.50	5.46

Note: Modal split =  $\frac{\text{auto patronage}}{\text{transit patronage}}$

Table 25

Gross Hourly System Cost in the Network Model

	1973			1990		
	\$1	\$3	\$5	\$1	\$3	\$5
Value of in-vehicle time:						
<u>Marginal Cost Pricing</u>						
Auto only	330.5	555.4	705.7	531.5	1,051.5	1,439.8
Auto vs. conventional bus	112.6	347.6	513.8	180.7	463.1	723.3
Auto vs. exclusive R-0-W bus	75.9	195.0	322.1	120.9	309.9	543.5
Auto vs. priority bus	75.9	195.0	318.4	120.9	309.9	527.3
Auto vs. rapid rail	105.3	324.3	469.5	166.1	416.7	612.5
<u>Perceived Cost Pricing</u>						
Auto only	330.5	555.4	705.7	531.5	1,051.5	1,439.8
Auto vs. conventional bus	171.8	400.9	595.7	217.6	571.0	891.9
Auto vs. exclusive R-0-W bus	75.9	321.2	530.5	120.9	409.2	725.5
Auto vs. priority bus	75.9	312.8	508.8	120.9	394.3	688.6
Auto vs. rapid rail	192.3	393.8	570.1	235.0	540.6	794.6

Note: Figures are in thousands of 1973 dollars per hour.



Table 26

Compound Rates of Growth of Various Economic Indices

<u>Index</u>	<u>Rate</u>	<u>Period</u>	<u>Source</u>
Consumer price index	4.6%	1967-1972	<u>Handbook of Labor Statistics 1972,</u> US DOL, BLS
Per capita GNP in current dollars	6.6%	1950-1969	<u>Handbook of Labor Statistics 1972,</u> US DOL, BLS
Motor coaches	3.2%	1967-1972	<u>Wholesale Prices and Price Indices, US DOL,</u> BLS
Highway construction	6.2%	1967-1971	<u>Price Trends of Federal-Aid Highway Construction,</u> US DOT, FHA, 1972
Rail transit vehicles	6.3%	1950-1970	<u>Institute for Rapid Transit Data Books 1,</u> 2 and 3
Local transit union wages	5.9%	1960-1971	<u>Handbook of Labor Statistics 1972,</u> US DOL, BLS
Electricity prices	1.3%	1960-1971	<u>Handbook of Labor Statistics 1972,</u> US DOL, BLS
Motor fuel prices	1.3%	1960-1971	<u>Handbook of Labor Statistics 1972,</u> US DOL, BLS
New auto prices	1.8%	1965-1971	<u>Handbook of Labor Statistics 1972,</u> US DOL, BLS

related to growth in per capita GNP. It can be seen from this table that the dollar valuation of per capita GNP, highway construction, rail cars and bus and rail transit operator's wages have increased at similar (current dollar) rates in recent periods. The prices of motor coaches, autos and petroleum fuel have increased at slower rates historically, but are not likely to behave similarly in the future because of tightening supply and environmental regulation policies. There have also been qualitative changes in nearly all of the inputs: rail transit and bus operator's unions have probably influenced the effective hourly rate of wage in a way not reflected in the time series; buses and autos are different substantially in operating and maintenance performance; rail car quality has changed substantially with higher passenger amenity levels but probably lower mechanical reliability if the BART experience reported in Chapter 6 is typical. Rather than venturing into assumptions of probable futures of these prices, 1973 input prices were used in the 1990 simulation. The results of the 1990 simulation are in Tables 24 and 25 as well.

The results of the network simulation show much of the same ranking of modal splits and system costs as did the simple path simulations; the direction and order of the sensitivity of the results to assumptions in environmental parameters is very similar. The automobile is a more effective competitor for patrons from conventional-type bus service and rapid rail transit than it is for the patrons of exclusive lane bus services. This can be seen by the dimensions of the modal splits presented in Table 24. The simplicity of the network structure and the monolithic nature of

the environmental parameter assumptions tends to make the modal split figures unrealistic; in reality, all of the parameters of the model -- trip length, access distance, user time valuation, even gasoline prices -- have (unknown) distributions. Assumptions of single values for these parameters disguises the presence of groups of travellers confronting atypical travel environments. Nonetheless, the various modal alternatives perform in significantly predictable ways under a wide range of parameter value assumptions in the network. Thus, while a modal split (ratio of equilibrium auto trips to equilibrium transit trips) of zero is an unlikely occurrence in a real-world context, the relative ability of one modal combination over another to tend toward a lower average level of automobile usage under various assumptions of time value and pricing regime is adequately displayed in this simple, but overstated way. Thus the ability of the exclusive lane bus technologies to attract auto patrons is consistently stronger than any of the other transit alternatives under any of the time-value or pricing regime assumptions. The effectiveness of rail rapid transit in maintaining low auto/transit usage ratios, while less than the exclusive lane bus technologies, appears to be less elastic as the time values increase than the conventional bus alternative. The modal split in the 1973 simulation for the conventional bus technology alternative under a marginal cost pricing regime, for example, changes from .95 to 4.07 as the value of time increases for \$3 to \$5 per hour of in-vehicle time, while the modal split for the rail transit alternative changes from .67 to 1.97. The

implied arc elasticity<sup>1</sup> of modal split with respect to time value is 2.85 for the conventional bus versus 2.11 for rapid rail transit. This is a manifestation of the effect found in the simple path simulations that the faster line-haul speeds of the rail transit technology are of value to users with high perceptions of time value.

Similarly, the priority lane version is relatively more effective at maintaining a low ratio of auto usage to transit usage as time values increase because of the compound effect of increased user valuation of the congestion experienced on the (reduced capacity) auto facilities and the high line-haul service speeds of the technology. Thus under perceived-cost pricing, the modal split for the exclusive right-of-way version increases from 2.1 to 7.08 while that for the priority lane bus service increases from .75 to 1.7; the arc elasticity of the modal split with respect to time value is 2.38 and 1.6 respectively.

The network analysis also sustains the implication of the earlier analysis that the extant pricing regimes (called here "perceived cost pricing") prejudices modal splits strongly toward automobile usage. The modal split ratios in Table 24 are consistently higher under assumed perceived cost pricing than under a social incremental cost regime (marginal cost pricing).

As transportation demand increases from the levels assumed in 1973 to that anticipated in 1990, the modal split shifts substantially in favor of transit. This is, of course, an expected

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<sup>1</sup> Defined here as 
$$\frac{\log(\text{modal split}_2)}{\log(\text{modal split}_1)} \div \frac{\log(\text{time value}_2)}{\log(\text{time value}_1)} \cdot$$

consequence of the assumption of fixed roadway capacity; as demand increases, the relative generalized cost of handling additional patronage on a fixed capacity roadway raises rapidly. The alternative of expanded roadway capacity probably becomes a viable one at some point, but this option will have to be explored by other investigators. We are interested here in presenting actual transit alternatives in an environment which gives them greatest benefit of reasonable doubt concerning public acceptability of non-transit alternatives.

As in the case of path model simulations, we are concerned primarily with economic feasibility, of which modal split is an uncertain indicator. Table 25 presents the total (variable) system costs of the various alternatives. As the figures in the tables attest, the ranking of transit alternatives (in terms of generalized operating costs) that was found in simple path analyses is sustained in the network analysis. The integrated bus technologies appear to offer substantial operating cost advantage over rail transit and conventional bus service, with the priority lane again appearing slightly less costly than the exclusive right-of-way version in spite of reduced roadway capacity-related auto congestion costs.

Of the "inferior" technologies, rail transit service appears to be cheaper (in these variable generalized operating costs) than conventional bus service at high user time valuations, but appears costlier at low (one dollar per hour in-vehicle time value) values of user time when perceived cost pricing is used in both the 1973 and 1990 simulations.

The sensitivity of the network modal split and system cost

figures to different assumptions about the value of users' time is testimony to the perilousness of allowing feasibility analysis to be performed outside the realm of sensitivity analysis. Most feasibility analyses (BART's included) are presented without reference to the sensitivity of the results to the assumptions. The relative simplicity of this network analysis makes the potency of assumptions somewhat clearer than a more detailed model in which the effect of the various assumptions would be disguised in the general complexity of the model; however, the assumptions are no less relevant in the analyses that have been applied to transit planning problems elsewhere.

As Table 27 demonstrates, all of the transit mode alternatives offer significant generalized operating cost savings over a pure automobile environment. However, in the San Francisco Bay Area, the decision to invest in the BART system was made in the context of an existing conventional bus system. Hence, the proper context of cost-effectiveness analysis is one which assesses to a BART-like system the benefits of user cost savings measured relative to the costs of the conventional bus service. The "conventional" bus service modelled in this study very likely organized according to more sophisticated rules than the bus system in existence at the time of BART's early planning.<sup>1</sup> Hence, again, the relative cost savings of the various modal alternatives are of more significance than the absolute values. In Table 28, the operating cost savings over conventional bus service offered by the exclusive lane bus modes and rail transit modes have been calculated for the various

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<sup>1</sup>The Key System, a private stock bus company.

Table 27  
Hourly Cost Saving When Replacing Pure Automobile Service with Other Modes\*

Value of in-vehicle time: Marginal Cost Pricing	1972				1990				
	\$1	\$3	\$5	\$1	\$3	\$5	\$1	\$3	\$5
Auto vs. conventional bus	217.9	207.8	191.9	350.8	588.4	716.5			
Auto vs. exclusive R-0-W bus	254.6	360.4	383.6	410.6	741.6	896.3			
Auto vs. priority bus	254.6	360.4	387.3	410.6	741.6	912.5			
Auto vs. rapid rail	225.2	231.1	236.2	365.4	634.8	827.3			
<u>Perceived Cost Pricing</u>									
Auto vs. conventional bus	158.7	154.5	113.0	313.9	480.5	547.9			
Auto vs. exclusive R-0-W bus	254.6	234.2	175.2	410.6	642.3	714.3			
Auto vs. priority bus	254.6	242.6	196.9	410.6	657.2	750.9			
Auto vs. rapid rail	138.2	161.6	135.6	295.5	510.6	645.2			

\* The cost savings compared with an all auto environment. Assumes 250 commute days per year and 6 commute hours per day. Figures are in thousands of 1973 dollars per hour and represent commute travel only.

Table 28  
Net Hourly Cost Saving of Replacing Conventional Bus Service with Other Modes\*

	1972					1990			
	\$1	\$3	\$5	\$1	\$3	\$5	\$1	\$3	\$5
Value of in-vehicle time:									
<u>Marginal Cost Pricing</u>									
Auto vs. exclusive R-0-W bus	36.7	152.6	191.7	59.8	153.2	179.8			
Auto vs. priority bus	36.7	152.6	195.4	59.8	153.2	196.0			
Auto vs. rapid rail	7.3	23.3	44.3	14.6	46.4	110.8			
- bus op. cost	62.6	31.3	12.5	78.6	46.2	23.0			
<u>Perceived Cost Pricing</u>									
Auto vs. exclusive R-0-W bus	95.9	79.7	62.2	96.7	161.8	166.4			
Auto vs. priority bus	95.9	88.1	83.9	96.7	176.7	203.0			
Auto vs. rapid rail	-20.5	7.1	22.6	-17.4	30.1	97.3			
- bus op. cost.	46.3	6.8	1.7	66.0	20.7	7.4			

\* Figures are in thousands of 1973 dollars per commute hour.



time value and pricing regime assumptions of the network simulations. The BART-like technology offers the least substantial cost savings and, in fact, at low values of time at the 1990 level of demand, appears to be costlier than the conventional bus alternative, at least as it is modelled in this study. The exclusive lane bus alternatives seem to have the greatest potential for offering the community the benefits of reductions in travel costs. The cost savings are variously two to six times as great per commute hour by these modes than by the rail transit alternative. As the value of time increases, the operating cost savings offered by rail transit grow relatively more rapidly than those generated by the exclusive bus alternatives. This is a reflection of the relatively more rapid decline in unit costs on the rail system because of its generally lower loads in the range of the experimental data; as time values increase and the relative line-haul speed advantage of rail transit (over the automobile and conventional bus) begins to take on value, the modal split disadvantage does not grow as rapidly as it does for the bus technologies. Thus relatively "more" of the rail technology's scale economies are exploited at high time values than in the case for the bus modes.

These effects are only relative changes in rates, however, and throughout the range of parameter values assumed in the simulation, the operating cost savings potential of rail transit are weak in an absolute sense.

We have yet to compare the stream of operating cost savings with those modal costs that are independent of system usage, namely costs of capital and other fixed costs of operation. In the case

of rail transit, there are the capital costs of way and structures in addition to fixed operating costs as the statistical analysis of Chapter 5 revealed. For the exclusive right-of-way bus, the capital costs of the busway structure must be assessed along with some costs of operating and maintaining the structure. The costs of providing the road surface for the priority lane version of the exclusive bus lane technology are more debatably defined. Since we are comparing here the change in system costs from one modal combination to another and the total road surface used has not increased, no additional assessment of basic roadway capital costs is called for. There are undoubtedly, however, additional costs to be incurred as a consequence of the exclusive use of freeway lanes by high-speed buses. The road surfaces and structures may require reinforcement due to more intense use by heavier vehicles or the life of the capital may be reduced; it may be necessary to construct special access ramps and other devices to isolate the flow of other vehicular traffic from the stream of bus traffic. As an extreme measure of these additional costs, we have used the full cost of the lane as estimated in Chapter 3. Table 29 displays the fixed cost assumptions for each of the modes at interest rates of six and twelve percent annualized over the anticipated life of the facility. For both the busway and freeway lanes, Meyer, Kain and Wohl's assumption of a life of 35 years is used to annualize the capital costs assuming constant productivity of the capital. The same total length of line-haul facilities is assumed for each of the modes (150 one-way miles). The conversion of annual costs to hourly costs is based on the extreme assumption that the costs

Table 29  
Fixed Costs of Network Transit Alternatives  
 (in thousands of 1973 dollars)

	<u>Rail Transit</u>	<u>Busway</u>	<u>Priority Bus</u>
Total Capital Costs	\$1,345,892.00	\$300,000.00	\$91,800.00
Annualized, at 6%	85,050.00	21,000.00	6,300.00
Annualized, at 12%	162,030.00	37,000.00	11,200.00
Annual fixed operating and maintenance expenses	16,500.00	600.00 <sup>1</sup>	---
Total annual fixed costs			
At 6%	101,550.00	21,600.00	6,300.00
At 12%	178,530.00	37,600.00	11,200.00
Total hourly fixed costs			
At 6%	67.7	14.4	4.2
At 12%	119.0	25.1	7.5

<sup>1</sup> Assumes that a mile of busway is as costly to operate and maintain as the average mile of urban road. Data source: Highway Statistics 1970, US DOT, FHA.

are entirely allocable to the peak periods of the roughly 250 work days per year. Ex post allocations of cost between peak and off-peak periods are arbitrary in a cost-effectiveness or economic feasibility analysis; the proper aggregate of peak and off-peak benefits should be compared with the entire capital costs of the project. The project alternatives being considered potentially serve (by assumption) identical user populations in the off-peak period; they are also of a basic service configuration that emphasizes interurban, commute trips and not the localized, many-to-many trip-making origin/destination patterns that characterize the off-peak period. Thus relative to the peak period, trip-making on these alternatives in the off-peak is likely to be quite small and tend to yield small off-peak benefits; a fortiori the mode that yields greater traveller cost savings in the commute mode is likely to be more effective serving off-peak travel demands that conform to peak travel patterns. The bus alternatives have an inherent flexibility that the rail mode lacks in that the vehicles may be dispatched to local street service and serve the varied off-peak travel patterns more effectively than a route-inflexible mode like the rapid rail transit alternative. Thus rail modes exhibit the greatest "peakiness" of demand for their services. Meyer, Kain and Wohl [ 74 , p.95] provide evidence that the automobile provides service for (and may have produced) the greatest relative off-peak to peak trip-making, followed by city bus systems, rapid rail transit, and finally, a commuter railroad, of which a BART-type technology and route configuration is a modern example. Thus even in the presence of good off-peak travel behavior data, the cost allocation presumed in

Table 29 is a useful extreme assumption in a comparison of commute technology alternatives.

The excess of hourly operating cost savings presented in Table over the hourly capital cost allocations of Table 29 to determine the economic feasibility of the alternative technologies being analyzed in this study. That is, the comparison of the stream of benefits (generalized operating cost savings) with the capital costs (converted to flows) of the various alternatives will provide an indication of the relative surplus of social benefits over social costs. In Table 30, the net social surplus has been calculated for the various parametric assumptions of the simulations and for the interest rates of 6% and 12%. With the additional assessment of fixed operating and capital costs, the rapid rail transit alternative appears to be at a severe disadvantage in this feasibility analysis relative to the bus technologies.<sup>1</sup> At nearly all values of time and under both 1972 and 1990 demand assumptions, the modelled cost savings that might accrue to the community as a consequence of an investment in a rail transit system are exceeded by the costs of the necessary capital and operations overhead. Assuming high valuations of user time (\$5 per hour of in-vehicle time, relevant to an average user income of about \$25,000 a year) at the level of

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<sup>1</sup> It should be re-emphasized that the relative social surpluses are of more importance than their absolute value. There is a slight chance that the social losses generated by the rail transit alternative could be offset by off-peak benefits or by relaxation of some of the simplifications inherent in the modelling, such as the assumption of a fairly sophisticated existing conventional bus system. While in other aspects of the model we have attempted to pari passu favor the rail transit alternative, these results (or any benefit-cost analysis) can only be tenuously used as a definitive statement of the infeasibility of the rail transit alternative.

Table 30  
Excess of Hourly Benefits over Hourly Costs in the Network Model\*

Value of in-vehicle time: <u>Marginal Cost Pricing</u>	1972		1990			
	\$	\$3	\$5	\$1	\$3	\$5
Auto vs. exclusive R-0-W bus	22.3 (11.6)	138.2 (127.5)	177.3 (166.6)	45.4 (34.7)	138.8 (128.1)	165.4 (154.7)
Auto vs. priority bus	32.5 (29.2)	148.4 (145.1)	191.2 (187.9)	55.6 (52.3)	149.0 (145.7)	191.8 (188.5)
Auto vs. rapid rail	-60.4 (-111.7)	-44.4 (-95.7)	-23.4 (-74.7)	-53.1 (-104.4)	-21.3 (-72.6)	43.1 (-8.2)
<u>Perceived Cost Pricing</u>						
Auto vs. exclusive R-0-W bus	81.5 (70.8)	65.3 (54.6)	47.8 (37.1)	82.3 (71.6)	147.4 (136.7)	152.0 (141.3)
Auto vs. priority bus	91.7 (88.4)	83.9 (80.6)	79.7 (76.4)	92.5 (89.2)	172.5 (169.2)	199.1 (195.8)
Auto vs. rapid rail	-88.2 (-139.5)	-60.6 (-111.9)	-45.1 (-96.4)	-85.1 (-136.4)	-37.6 (-88.9)	29.6 (-21.7)

\* Figures are in thousands of 1973 dollars per hour using 6% discount rate. Figures in parentheses involve use of a 12% discount rate.

demand anticipated in 1990, the rail transit alternative displays a positive social surplus, but is dominated in every instance by the surplus generated by the exclusive lane bus alternatives. Of the two alternative bus technologies, the priority lane dominates the exclusive right-of-way version because of the lower additional capital requirements of this mode.

While an effort has been made throughout this research to test the economic viability of rail transit under conditions which are generous toward that mode, there are some biases against rail transit inherent in the analysis and they should be assessed at this point.

There are certain characteristics of the BART system which should not be ascribed to rail transit systems in general. For example, it was noted that the BART system configuration did not permit breaking up of 10 car trains to accommodate a diurnal load cycle. If it were possible to break up trains in precise coordination with the patron loads during various times of the day, as much as 50% of the annual vehicle miles produced might be spared. However, the magnitude of this saving is not large because of the heavy proportion of fixed operating and capital costs of the BART system. From Table 13 in Chapter 5, saving 12.5 million car miles annually (50% of the prospective full system output) would yield annual operating cost savings of roughly \$9 million. This amounts to about \$6000 per peak hour of operation. Comparing this figure with the losses incurred per hour by rail transit in Table 30 demonstrates that this is not likely to influence the judgement of the economic viability of a BART-like system.

A second potential bias in the analysis relates to the assumed capital costs of the BART-type vehicles in the rail transit model. For both bus and rail transit vehicles, the network analysis assumes a per-vehicle mile capital cost based on the total annual utilization of the vehicles, rather than allocating these costs entirely to the peak hours of use.

In the case of the rail transit vehicles, this allocation differs from the procedure that allocates all vehicle capital charges to the peak by a factor of something between three and five. The vehicle capital charges assumed in the simulations would have to be multiplied by 3 to 5 if the rail transit management's fleet decisions are entirely determined by peak period demands. Assuming a lower value will tend to model a vehicle dispatching policy that encourages large vehicle fleets; optimal train dispatch policy will imply deployment of more trains per peak hour than would the alternative allocation of all vehicle capital costs to the peak hours. In the models, the higher frequency will then lead to an overstatement of user benefits, and an overstatement of fleet needs. A bound on the effects of allocation of all vehicle costs to the peak is easily obtained, however, by calculating the maximum system cost savings of eliminating the non-economical fleet. The fleet decision making embodied in the network simulation is in fact wasteful. What would be the system cost savings of eliminating the excess fleet? These savings will certainly be less than the cost of the full fleet per hour and will thus be the maximum cost savings anticipated. Allocating the entire capital cost of the rail vehicle fleet to the peak hours



will, hence, give us a useful bound on the degree to which net system benefits for the rail transit system are understated. Table 31 below gives the hourly costs of fleets of BART-type vehicles of various reasonable sizes.\*

Table 31  
Cost of a Rail Transit Vehicle Fleet  
 (in thousands of dollars per peak hour)

<u>Interest rate</u>	<u>Fleet Size</u>		
	<u>400 cars</u>	<u>500 cars</u>	<u>600 cars</u>
6%	6.7	8.4	10.0
12%	10.9	13.6	16.3

Taking these figures as an indication of the maximum system cost savings available through more conservative vehicle deployment policies, they may be added to the net benefit figures of Table 30 to derive the more optimistic estimate of net system benefits of the rapid rail system. Note that these savings are generally small relative to the "deficit" suffered by the rail alternative under most time value assumptions. More importantly, they are small relative to the differential between the net system benefits of the rapid rail alternative and the other technologies. Of course, using an alternative assumption concerning allocation of bus capital costs would affect the calculated differential as

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\*The computer model above does not generate any data with regard to fleet requirements except the equilibrium headways between trains. Actual vehicle requirements depend upon hostling and maintenance procedures which we are not able to optimize in detail. Hence we assume that the fleet will be roughly the size of the projected BART fleet at similar headways.

well. However, the elasticity of total bus operating costs with respect to capital costs was found (in Chapter Four) to be only about .07, making the effect of a different allocation procedure on the simulations much less significant. Buses tend also to serve more significant midday markets, making allocation of all capital costs to the peak somewhat suspect even as a long run marginal estimate. Again, the differences are so great that different capital cost accounting methodologies will not affect the basic ranking observed in the simulations.\*

In fact, if one could rely heavily on the calculations presented in this chapter, there is some evidence that abandonment of the existing rapid rail system would be justified. The negative net benefit calculations presented in Table 30 indicate that the community will take an economic loss if such a system is constructed as a replacement for an existing conventional bus system. In order to assess the viability of abandonment, however, the system cost savings of replacing the rapid rail system with an alternative must exceed the capital costs of constructing the alternative. Table 25 above details the gross hourly system cost of the various alternatives. In general, abandoning the rapid rail system in favor of a conventional bus system does not appear viable because the system costs of the conventional bus system exceed the system costs of the rapid rail alternative. Abandonment would entail net economic losses in that

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\*For example, the difference between net system benefits of priority bus and rapid rail in 1972 at 6% and \$5 per hour is \$124,000 per hour. In order to accommodate this difference, an alternative capital accounting methodology would have to assign the capital cost equivalent of nearly 60,000 buses to the peak.

case. However, the system costs of both the priority and exclusive right-of-way versions of the integrated bus transit technologies are less than the rapid rail alternative. The fixed costs of these alternatives (as presented in Table 29) are, in general, not larger than the difference in system costs between themselves and the rail alternative, suggesting that abandonment in favor of one of those alternative bus systems is economically feasible. Table 32 presents the calculation of the net benefits of abandonment for the two special bus transit alternatives.

Table 32

The Net Benefit of Abandonment of an Existing Rapid Rail System

		1973	
Value of in-vehicle time:	\$1	\$3	\$5
<u>Net System Cost Savings</u>			
Replacement with priority bus			
At 6%	25.2	125.4	146.9
At 12%	21.9	122.1	143.6
Replacement with exclusive R-O-W bus			
At 6%	15.0	114.9	133.0
At 12%	4.3	104.2	122.3

Note: Figures are in thousands of 1973 dollars per hour.

## CHAPTER EIGHT

## CONCLUSIONS

This research has attempted to develop and demonstrate a methodology for comparing the relative social costs of satisfying urban commute travel demands by means of various modes and modal combinations. The method used to overcome the problems inherent in feasibility assessment in a multi-product environment was to subsume qualitative output difference in expanded or "generalized" cost functions; the attributes in output space were converted to user-supplied commodities in input space. While the resources available to this researcher confined the experimentation with the methodology to fairly simple paths and networks, we demonstrated the relative ease with which it enables analysis of the feasibility of real transportation alternatives. With more complete data on travel behavior and more detailed networks, this analysis lends itself to much more rigorous treatment of transportation planning problems than other methods of analysis permit. The analysis of Meyer, Kain and Wohl, while a seminal effort, suffered from an incomplete description of the output space of urban transportation technologies. Edward Morlok's analysis, employing a more complete characterization of the unit of output of the various modes, functions in multi-dimensional output space and does not offer the potential for convenient multi-modal flow equilibration and feasibility analysis of the current methodology.

The current method of analysis, while subject (like all models) to dependency on parametric assumptions, does not rely heavily

on the modification of modal attributes to accommodate the non-comparability of the products of different urban transportation technologies as the Meyer, Kain and Wohl methodology does. Nor does it require particularly severe simplifications of the description of the service characteristics of modal alternatives; it allows transfers among modes, flow interactions among modes and transport networks as complex as data and computational capability permit.

This study was conducted in the environment of a major regional transit investment, the BART system. Much effort was expended acquiring serious estimates of the costs of providing the services of such a technology, this being a relatively unexplored area of cost function estimation. The bulk of the analytical work was framed in the context of exposing the rail transit alternative and all other alternatives to a sufficiently wide range of important parameter values so that overlaps of the feasible regions of operation of the various modes could be discovered if they existed.

We have made a deliberate effort in this research not to be tempted to reduce the analysis to a single measure of feasibility, leveraged on a series of generous or tenuous parameter assumptions. Rather, we have preferred to argue by a fortiori reasoning, wherein the potentially weakest alternative is given the benefit of some doubt in assumptions of parameter values and model restrictions. This is not to deride these investigators (and we are among them) who have been forced to simplify and make tentative assumptions in their analysis, but the conclusions in this analysis, we believe, have been strengthened by framing the investigation in this manner, rather than destabilizing the analysis with tenuous detail and weak

data. Thus while modelling the performance of the various alternatives in the off-peak and developing estimates of off-peak cost savings would have enabled us to avoid the allocation of transit capital costs entirely to peak benefits, the results would have been leveraged on a particularly tenuous body of data; these assumptions serve both to maintain a reasonable dimension to our task and give it a specific posture on which to base conclusions about the relative, if not absolute, capabilities of the various modes.

The path and network analysis demonstrated that within a wide margin of parameter assumptions, the rail transit alternative is dominated by the bus modes; the community is likely to experience greatest cost savings from introduction of the high-speed bus alternative. While the line-haul portion of the rail transit alternative has lower incremental seat-mile costs at high patron densities than the bus alternatives, the costs of access and the fixed costs of providing the service are high enough to make high-speed bus alternatives more attractive under nearly all conditions of demand and assumptions of time values and trip description. While the rail transit alternative performs relatively better under circumstances of high time value, high levels of demand (and heavy congestion on automobile facilities) and short access distance, high speed bus alternatives appear to perform at least as well under these same conditions and on a considerably smaller capital outlay.

Of the bus alternatives, the exclusive right-of-way and priority lane versions appear to offer substantial potential for reducing the social cost of commute travel, even in comparison to a hypothetical, optimally dispatched and routed conventional bus

service. The priority lane concept appears to be the preferred alternative when the costs of the freeway lane conversions are competitive with busway construction, as they are likely to be in most circumstances and when the lane reduces one-way freeway lane capacity by 20-25% as in the simulations.

This research, then, appears to make an unambiguous statement concerning the economic viability of a heavy, fixed rail technology relative to certain transit bus configurations. It should be kept in mind that the analysis has necessarily proceeded in an abstract and schematic way, and the results are themselves, therefore, hypothetical. However, the evidence indicates the type of forces at work and will, I hope, prompt cities to undertake more thorough consideration of transit alternatives before embarking on a massive fixed rail investment.



APPENDIX A  
THE VALUE OF TRAVEL TIME

The significance of time savings in considerations of transit or other passenger transportation alternatives has generated a substantial body of data on the rate at which time should be valued. In early studies, travel time undifferentiated by the type of activity or type of travel was the primary emphasis of research, but more recent work has attempted a functional disaggregation of time values in recognition of the important differences in user perception trip components. There are several major works in the literature which attempt a review of the myriad studies of the value of travel time, notably Nelson [1], Haney [2], and Hensher [3]. Hensher's is the most recent (1973) and omits few of the relevant studies performed before that time.

The basic methodology involved in valuing traveller's time is to observe consumer trade-offs between time and money and to infer statistically from these observations the relative willingness of travellers to trade one for the other. The data for the commuter case generally consists of observations on the choice of mode, although Mohring [ 4 ] and Wabe [ 5 ] used the trade-off between travel time and real estate site value to derive their estimates, Dawson [ 6 ] used route choice, and Lisco [ 7 ], in a portion of his analysis, used the trade-off between parking charge observations and walking distance to derive values of walking time. The statistical techniques used to infer the rate of trade-offs occurring have included least squares regression (Wabe [5], Hensher [8],

and others), discriminant analysis (Quarmby [9], Thomas [10], and others), probit analysis [Lisco [7], Lave [11], and others) and logit analysis (Charles River Associates [12], McFadden [13], Dawson [6], and others).

The most careful analytical structure of these studies is probably that of McFadden, who is using mode choice data to infer rates of exchange between the money costs of the various modes and the service characteristics of the modes, including transfers, waiting, walking and in-vehicle time. He is using two-stage models to incorporate the simultaneity of the automobile ownership decision in the mode choice analysis. Attempts are also being made to stratify the estimates by user income class. Unfortunately, at this writing, only the results of a pilot study [13] are available and these results appear to be statistically of rather low quality; additionally, the small sample of 200 was an enriched sample drawn intentionally from areas with comparable levels of auto and transit use and the modal preference effects are not the population values. In general the sample size was too small to allow accurate estimates of the values of different types of travel time although the work is proceeding.

While the sensitivity of this study's work to a variety of time value assumptions will be explored, we are interested in the relationship between time value and user income so that the reasonableness of the range of assumptions may be assured. Further, the resources available to this analysis restrict the variety of relationships among trip time types that may be explored in the simulations. Table A-1 presents estimates of the relationships between time values and income and among trip time components generated by recent major investigations.

Table A-1

Summary of Major Studies of Commute Travel Time Values

Investigator	Date <sup>1</sup>	Value of Time ÷ Wage	Value of Other Trips Components ÷ Value of In-Vehicle Time
Mohring [4]	1948	.22 to .43	---
Merlin and Barbier [16]	1961	.60 to .75	1.75 to 3.0 (out-of-veh time)
Beesley [14]	1963	.31 to .49	---
Lisco [7]	1964	.52	2.7 (walking time)
Quarmby [9]	1966	.20 to .25	2.0 to 3.0 (out-of-veh time)
Rogers and Metcalf [17]	1966	.47 to 1.32	1.6 to 3.5 (out-of-veh time)
Thomas [10]	1967	.61	---
Charles River Associates [12]	1967	---	2.77 (walking time)
Lave [11]	1969	.42	---
Thomas and Thompson [15]	1970	.40	---
Hensher [8]	1970, 71	.19 to .27	1.5 to 2.0 (out-of-veh time)
McFadden [13]	1972	.50	1.3 to 1.6 (out-of-veh time)

<sup>1</sup>Refers to date of data collection, not publication.

As the data in the table suggests, the value of in-vehicle time is quite consistently estimated to be something less than the average wage of the observed population. The out-of-vehicle time components, such as walking or waiting time are generally greater than the in-vehicle time value by a factor of 2 to 3 times. Most of the studies that attempt to differentiate time components have produced results of low significance, however. Assuming that the estimates of the Thomas and Thompson study are the most relevant ones to a study in the San Francisco Bay Area (in-vehicle time value = two-fifths of the wage) and that (undifferentiated) out-of-vehicle time is equal to the wage, the implied income of the traveller is given in Table A-2 for a range of time value assumptions. The mean family income in the San Francisco SMSA in 1970 was \$13,429 according to the 1970 census.<sup>1</sup> With an average of 1.6 earners per family, the implied average income for a potential commuter is \$8393. The range of time values used in this study is within the range of conceivable time values for the Bay Area.

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<sup>1</sup>Source: US Department of Commerce, Bureau of the Census, 1970 Census Tracts SF-Oakland SMSA, Washington, 1970, Table P-4.

Table A-2  
Time Value and Income

<u>Value of In-Vehicle Time</u>	<u>Value of Out-of-Vehicle Time</u>	<u>Implied Annual Income</u>
\$ .50	\$ 1.25	\$ 2,500
1.00	2.50	5,000
2.00	5.00	10,000
3.00	7.50	15,000
4.00	10.00	20,000
5.00	12.50	25,000

Note: Assumes 250 8-hour work days annually.

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