Optimum Investment in Two-Mode Transportation Systems

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Proposals have been raised to tax use of highways in relationship to the volume of vehicles thereon. Aside from mechanics and legal questions, this raises the problem of methods of financing all means of transportation (for example, whether, as a matter of public policy, road users might be taxed to support rapid transit). Beyond this, the question of public investment in (or taxation of) transportation facilities is raised as it may affect property values; for example, in hastening the obsolescence of buildings. These are difficult questions, related both to public goals and to democratic and practical means for implementing them. The paper discusses these problems from the viewpoint of the transportation planner and the city planner.

• PROPOSALS have been made to tax the use of expressways so that higher taxes would be paid on more congested roads, or at more congested time periods on a given road (14). These proposals are based on the assumption that it is proper to take a limited view of one road at a time and to treat that facility as a monopolistic production apparatus whose profit should be maximized, or whose use should be held below some predetermined level by some pricing mechanism.

This narrow viewpoint cannot be taken by those whose business it is to make recommendations for transportation improvements for metropolitan areas. For such work it is obvious that consideration of gains and losses must be as complete as possible. For example, reductions in accidents in a broad band of a city resulting from the construction of an expressway is a demonstrated gain which should be taken into account in preparing plans (15). Congested use of expressways, although more costly to all users of expressways, may be at a per mile cost level substantially below that of travel on arterial and local streets, and hence may provide over-all reductions in cost to the whole community (16).

It would appear that pricing of transportation facilities ought not to be considered without a simultaneous or even prior consideration of the costs and benefits of supplying new transportation facilities. And this investigation ought to consider the various types of new facilities which should be provided. This, in turn, calls for a basic understanding of the selection of mode of travel by persons living in urban areas.

This paper, therefore, addresses itself to the problem of investment in transportation facilities, both for individual and group modes of transportation. (Throughout this paper "individual" transportation is treated as synonymous with automobile transportation; "group" transportation is used for so-called "mass transportation"—that is, buses, rail rapid transit, and suburban railroads.) This is a problem of intense interest to planners. An investigation of optimum investment policies produces insights which will be helpful in considering appropriate policies for the taxation or pricing of transporta-

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tion. The question of maintenance and management (or control) of existing transportation facilities is not considered, other than through taxation or pricing, and this latter is only discussed at the end of this paper. Furthermore, the scope of this paper is restricted to the transportation of persons within urban regions by individual and group modes of transportation.

The "investment problem" assumes that a metropolitan society and its nation or state has a surplus of funds available for investment. This investment may be either in capital facilities or in the form of subsidies for the continued operation of some service. The transportation investment problem is the problem of deciding:

1. How much investment should be made in transportation, as opposed to other possibilities for investment, either public or private.
2. What mode (that is, bus, rail rapid transit, or road system) should receive investment funds, and in what proportion.
3. When the investment should be made.
4. Where the investment should be made.

The transportation investment problem is made more difficult by the fact that it is a geographic as well as a financial problem. The buying and selling of transportation services (for example, the seat-mile of bus service or the vehicle- or seat-mile of automobile service) is accomplished over the surface of large metropolitan regions and not in the non-dimensional (and non-existent) "perfect market." Clearly, the facts of space and spatial distribution affect the investment problem. Also, there is the problem of skillful design: a given level of investment in roads can be profitable or unprofitable depending on the skill with which it is laid out. This calls for a team approach (using both economists and planner-engineers) both in studying investment and in planning the facilities.

The remainder of the paper develops an approach for the examination of this question. This is done by first studying a series of goal systems: those of the transportation user, those of the land-based entrepreneur, and those of metropolitan management. Next, the user's viewpoint is examined, both as to the amount of transportation purchased and as to the type of transportation selected. Then the investment problem is analyzed from the viewpoint of metropolitan management and, finally, conclusions are reached.

GOALS

It is assumed that there are three sets of goals: those of the user of transportation, those of persons in their land-based activities, and those of metropolitan management. "Metropolitan management" assumes a top level metropolitan, or perhaps state, viewpoint. Naturally, these sets of goals are not separable in real life because the land-based entrepreneur is also a traveler, and in both capacities he is a voter influencing metropolitan management.

The Transportation User

The goal of the transportation user is taken to be economic: to minimize the sum of his transportation costs in relationship to the reward he will obtain from traveling.

Transportation is viewed as a cost item. The costs include money outlay (transit fares, auto and truck operating costs, vehicle ownership costs, etc.), time outlay, the risk of accidents, and discomfort of various types. Only rarely is urban transportation per se undertaken as a reward in itself—about 1 percent of all trips are "ride" trips (1)—hence, the cost viewpoint is reasonable.

Obviously people do not expend money, time, risk, or discomfort unless they hope to gain a return. The rewards of traveling lie in the gains to be made at the destination of each trip, and include such things as wages and salaries, and recreational or residential satisfactions. These will be different in amount for different people and will vary by trip purpose. Over time these gains and satisfactions may be expected to rise, as long as productivity continues to rise.

Travel is seen, then, as a cost item to be expended for a return of some type. For example, a person will spend more (travel farther) for a good job than he will for a lower paying one, and he will travel farther to purchase a sofa than a loaf of bread. Naturally, the length of each type of trip is also a function of the locational patterns of various enterprises, which in turn is affected by the economics of production and distribution.

The Site User

The person undertaking some activity on a particular site—a retailer in his store, a manufacturer in his plant, a housewife at home—has the same basic goal as the person in motion but it is expressed differently. The goal is to maximize gains, whether they be the profits of commercial and industrial activity or the satisfactions of residential or recreational activity.

The site user's gains include such things as wages and salaries, residential and recreational satisfactions, profits from business and industry, and the possession of goods purchased at a site. These gains come whether the person is a permanent site user (for example, an owner or renter) or a temporary site user (for example, an employee or customer).

The site user's costs include such things as labor costs, material costs, taxes, money paid for goods or services purchased on the site and, of course, transportation costs of all types.

For the site user to maximize his gains he must first choose a site and then manage it or do business at it or work on it or live on it. The site selection process is a complex calculus of alternate site costs, taxes, community services, environment, location with respect to market or labor force, and transportation costs. Site occupancy involves decisions on investment in buildings, grounds and equipment, how to get ahead on one's job, what goods to purchase, and so on.

An important point here is the relative importance of transportation costs to all other costs of the site user. Probably transportation costs are not less than 10 percent, and rarely more than 25 percent of all costs, irrespective of whether the activities are residential, recreational, or employment activities. The non-transportation costs (and, by the same token, the rewards) are dominant. This is another way of saying that land use is a primary consideration which should be served by transportation facilities.

The much greater importance of the site-based costs and returns relative to those of transportation leads to the selection of densities of land development which will permit the site user to maximize his gains. For example, a long assembly-line building may be extremely profitable because it reduces labor costs, which are a high proportion of manufacturing costs. Travel requirements may be increased, due to the need to find a site large enough, but the over-all operation may become more profitable, even counting increased travel costs. Similarly, congestion in a wide area of a city may be a necessary price to pay for greater social productivity.

Metropolitan Management

The goal of metropolitan management is, broadly speaking, a social welfare goal: to maximize the metropolitan "product." (It might be desirable to add "and to insure an equitable distribution of the metropolitan product." However, distributional equity is beyond the scope of this paper.) In this instance "product" is construed to be broader than the traditional economic definition of the total goods and services produced. Maximization of product requires satisfaction of the demands and needs of the urban society for services, creation of an environment (or arena) in which the production of goods and services will be maximized, and promotion of the general health, safety, welfare, and amenity. Inevitably there are conflicts within these goals and, like the transportation user and the site user, metropolitan management must strike a balance between competing goals in order to optimize net gains to the entire community.

Without having perfect knowledge, or comprehensive understanding of all the factors, or the ability to account for all gains and losses, those who represent this viewpoint must be as careful and complete as is possible in the accounting they use in making decisions on investment.

The difficulty is that for a metropolitan investment, such as an expressway, the return may, like the bread cast on the proverbial waters, come in a myriad of ways at different, unpredictable future times. Investment selection is further complicated by the interdependent character of investment decisions both spatially and over time. One metropolitan investment will often call forth additional investments in related facilities and services; or the reaction to a metropolitan investment may, over time, create the need for an additional investment. Thus, provisions of a municipal water supply to a suburban area may, in the absence of other controls or actions, generate sufficient density of development to require municipal sewers and eventually new arterial streets. Clearly, each action of metropolitan management cannot be evaluated alone but must be accounted within a large enough reference to include interaction between items and over time and to include private or mixed as well as strictly public actions.

For the purposes of this paper, various sets of goals which together comprise the main goal of metropolitan management have been categorized. For convenience, these have been drawn up into two main parts—those connected with transportation and all other goals—as follows:

Non-transportation goals:

1. Increase in per capita production of goods and services, including housing.
2. Equitable distribution of social product.
3. Amenity.
4. Reduction of capital and operating costs of building and sites.
5. Increase in public knowledge of factors influencing development decisions.

Transportation goals:

6. Satisfaction of sum total of travelers' objectives (for example, to minimize travel time, costs, risks, and discomfort in relation to gains from travel).
7. Reduction of capital and operating costs of road and transit systems.
8. Satisfaction of other transportation objectives (for example, goods movement).

In addition, metropolitan management must aid individual decision making by increasing public knowledge of the potential effects of both public and private action in transportation and in the non-transportation areas. Also, it must inform the public of the range of alternative actions and their probable effects.

Viewpoint of Paper

The viewpoint of this paper is that of metropolitan management, and the focus is on transportation investment. Metropolitan management wants to decide how much to invest, what mode should receive what proportion, and when and where.

In making these decisions, metropolitan management assumes that travelers will seek to maximize the returns to be achieved from their daily expenditures in transportation. Put in other words, metropolitan management understands that, given the more stable and dominant locations of land-based activities, travelers will seek to minimize their transportation costs, each person freely seeking to minimize his own costs. A clear understanding of how the traveler's goal affects the purchase of travel is therefore necessary and is considered in a subsequent section.

The viewpoint of metropolitan management is necessarily long-range—that is, 20 to 30 years. In a period of this length, metropolitan management realizes that real wealth will substantially increase.

It is assumed that investment funds of some magnitude are available. Within such a time period, the accounting of gains and costs will be as complete as possible.

Metropolitan management is vitally concerned with the goals of site users—that is, with their desire to increase gains. Increasing site user gains, is, in the aggregate, the same as increasing the production of goods and services for the metropolitan community. This has been assumed as the single criterion for success in governmental policies.

To achieve this goal, metropolitan management has a variety of tools—taxation, spending, land control and regulation, and the intangible power of persuasive leadership. Transportation investment is among these tools. The problem, however, is that the effect of the single variable, transportation, on goods production, amenity and so forth, is difficult to ascertain. This paper does not consider explicitly the effect of transportation investment on non-transportation goals. Each year additional technical gains in the planning and decision making processes are being made; and it is hoped that gains will be made in considering non-transportation goals, just as it is hoped that this paper will provide a systematic way of evaluating the proper allocation of investment as between individual and group transportation.

CHOICE OF TRANSPORTATION MODE

In this section, the choice of mode of transportation is investigated from the viewpoint of the user, who is basically assumed to be an economic man in his choice of mode of transportation.

In order to treat choice of mode on the basis of cost analysis, the user is assumed to have good knowledge of vehicle costs, of operation and depreciation, and a knowledge of the time required to travel by the various modes of travel which are available. Tangible but immeasurable costs of travel, such as discomfort and inconvenience, are assumed to be incorporated with time as a cost. Thus the inconvenience of waiting at a station or stop for a group form of transportation is included within over-all journey time. Time in all cases throughout this analysis is taken as portal-to-portal time, and speeds are taken as journey speeds, which are considerably slower than vehicle speeds, inasmuch as they allow for walking, waiting, and parking. (It should be noted, however, that in the subsequent section on "Selection of Capital Investment Policy," in dealing with person-miles of travel some speeds used in computation are the speeds actually experienced on an express facility).

Because the authors take a long-run view of the life of a transportation facility, it follows that a long-run view should be taken in analyzing the costs of transportation when seen from the viewpoint of the user. Specifically this refers to a period lengthy enough to enable the user to exercise the option of whether or not to purchase an individual vehicle (automobile). In this analysis therefore, car depreciation and insurance are included in calculating transportation costs.

Throughout this analysis, the unit "person-mile of transportation" (PMT) is used. The use of this unit permits comparison of costs as between individual and group forms of transportation.

The costs of purchasing person-miles of transportation, by whatever mode, are composed of two parts: (a) movement costs and (b) time costs. Movement costs consist of fares in the case of group transportation. Fares may or may not cover all the costs of producing group transportation service; that is, of operating buses, subway trains, elevated trains, or suburban railroad trains. Nevertheless, they are the costs apparent to the user, and are the costs which he sees in making a decision as between modes. Movement costs in individual transportation include the costs of owning, operating, and insuring an automobile seat for one person. (If mean occupancy is 1.5 persons per vehicle, then vehicle-miles of travel costs are divided by 1.5 to obtain person-miles of travel costs.) Both movement and time costs are treated in the following.

Movement Costs

Although this paper is primarily concerned with developing improved methods for analysis and investment planning, these methods require some real measures, both to test reasonableness and in actual planning. It is in this sense only that the values given herein are used.

An urban situation was visualized in establishing preliminary working figures of transportation costs encountered by the user.

1. Both \$0.15 and \$0.25 fixed fares, without additional transfer costs, are assumed for buses and rail rapid transit (subway or elevated lines).
2. A charge of \$0.04 per mile is assumed for suburban railroad service.
3. Auto costs, at an average speed of 11 mph (implying driving under conditions of some congestion), are assumed as follows:

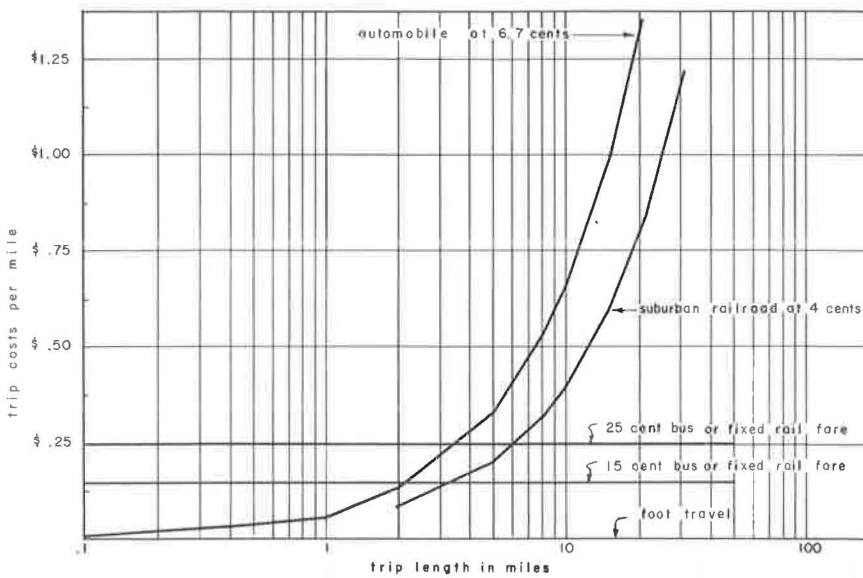

Figure 1. Comparative movement costs per person-trip by trip length and mode.

Item	Cost ($0.01/mi)
Variable cost (2):	
(a) Gas, oil, tires, brake wear, maintenance	4.41
Fixed cost (3):	
(b) Depreciation	2.54
(c) Insurance, registration, titling	1.49
(d) Parking, garaging	1.08
Total	9.52

This can be rounded off to $0.10 per mile, which for average occupancy at 1.5 persons per car, makes the per person costs $0.0667 per mile.

Figure 1 shows how trip costs rise when a person increases the length of a particular journey. Of course, if the purchase of round trip or daily journeys is considered, the price of the fixed-fare group transportation would have to be doubled or more, inasmuch as separate fares are required for each leg of a journey. Because it is not possible to consider the use of rapid transit or suburban railroad service for very short distances, Figure 1 does not portray these costs below 1- and 2-mi limits, respectively.

If these were the only considerations associated with selecting the amount and mode of transportation, the following points could be made:

1. All trips would be made on foot.
2. The next cheapest form of transportation would vary as a function of trip length:
   (a) Trips less than 2 mi long would be made by automobile (suburban railroads presumably would not be available for short journeys).
   (b) Trips between 2 and 3 mi in length would be made by suburban railroad.
   (c) Trips more than 3 mi in length would be made by bus or by rail rapid transit.

These points would be altered slightly depending on the cost figures used and the number of riders per car, but they do show that movement costs are not the only things considered by persons when choosing mode of transportation. Otherwise something more than the 28 percent of all trips now made on foot or the 6½ percent of trips to work on foot would be the rule (4). Granted the employment, recreation, shopping, and other opportunities which are spread over a modern metropolitan area, the person who walks barely has time to reach most of them on foot. Certainly he will have little time left over to participate in them. Because participation in these activities is rewarding, a person is generally willing to spend more for transportation in order to get within effective range of these activities.

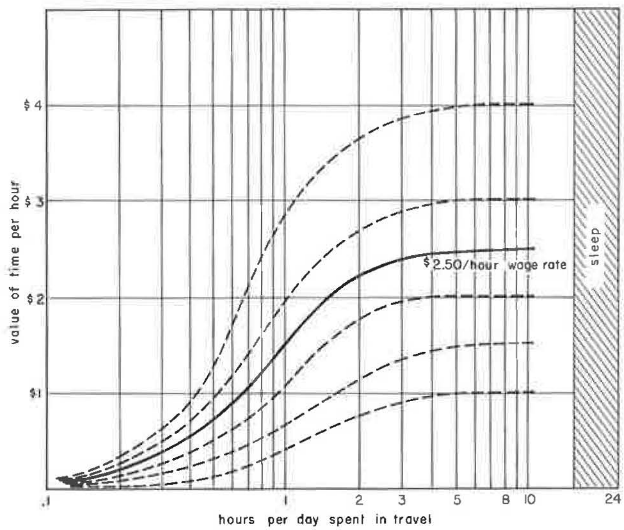

Figure 2. Individual's valuation of time.

Value of Time

This raises the question of the value of time. A number of studies have been made which set values for the time of automobile users. These studies recognize the difficulty of measuring the value of time because the results are averages—for persons with different incomes traveling for different purposes. Furthermore, most of these studies deal with choices between toll and free facilities on fairly long trips.

The authors suggest that there are two main considerations in an individual's valuation of his personal time. One is his income. The other is the amount of time spent each day in traveling. Because time is a scarce resource for most individuals, it seems reasonable to assume that the more time devoted to a particular activity, such as traveling, the more valuable it becomes. The reason for this is that less time is then available to devote to other activities.

This argument is depicted in Figure 2, which suggests that for small amounts of time (say, 5 min) devoted to travel, time has practically a zero value. However, when time per day devoted to travel exceeds 2 or 3 hr, its value becomes the value of the hourly wage of that individual. In Figure 2 the value used is $2.50, inasmuch as this approximates the mean national wage of production workers. The shape of the curve is purely intuitive.

Similarly, it can be argued that the more income a person commands, the higher the value he will place on his time, and the more he will be willing to pay for savings in traveling. This is suggested in Figure 2 by the family of curves leveling off at different hourly wages.

The preceding paragraphs are obviously not conclusive, only suggestive. Their first purpose has been to suggest that an increasing daily investment of time in travel is viewed as being at increased cost. Their second purpose is to suggest that the higher the person's income, the more highly he will value all time spent in travel. These ideas have a significant impact on the traveller's choice of mode and amount of travel.

Choice of Mode

Comparison of operating and time costs by mode of travel are extremely difficult and can be deceptive when analyzed on a single-trip, round-trip, or other short-term basis. Proponents of group and individual forms of transportation can produce figures which suggest that either form of transportation is less costly.

However, when costs are treated on a long-term basis, a much sharper and clearer picture of mode choice appears. This picture, furthermore, appears to be completely reasonable in the light of available evidence on mode choice (Table 1).

In Figure 3, the dotted line shows that the cost of purchasing seat-miles of transportation by group transportation is substantially lower over the range up to 15,000 mi per

TABLE 1

MOVEMENT AND TIME COSTS BY MODE

Miles Traveled	Cost ($)									
	Individual						Group			
	Base Auto Cost[a]	Movement at $0.03 per Mi[b]	Sub-total	Time at $0.91 per Mi[c]	Total	Per Mile	Movement at $0.057 per Mi[d]	Time[e]	Total	Per Mile
10	434	-	434	1	435	43.50	-	1	1	0.20
100	434	3	437	9	446	4.46	6	14	20	0.20
500	434	15	449	45	494	0.98	28	72	100	0.20
1,000	434	30	464	91	555	0.56	57	143	200	0.20
2,000	434	60	494	182	676	0.34	114	286	400	0.20
4,000	434	120	554	364	918	0.23	228	572	800	0.20
6,000	434	180	614	546	1,160	0.19	342	858	1,200	0.20
8,000	434	240	674	728	1,402	0.18	456	1,140	1,600	0.20
10,000	434	300	734	910	1,644	0.16	570	1,430	2,000	0.20
15,000	434	450	884	1,360	2,244	0.15	850	2,160	3,000	0.20
20,000	434	600	1,034	1,820	2,854	0.14	1,140	2,860	4,000	0.20

[a] Fixed costs divided by 1.5 persons per car.
[b] Variable costs divided by 1.5 persons per car.
[c] Auto journey, speed 11 mph (5); assumed $1.00 per hour value of personal time.
[d] Assumed $0.25 fixed fare divided by mean journey length of 4.4 mi, which is weighted combination of bus and subway-elevated passengers, Chicago area, 1956 (6).
[e] Assumed $1.00 per hour value of personal time; speed is 7 mph; which is weighted combination of bus and subway (elevated journey speeds).

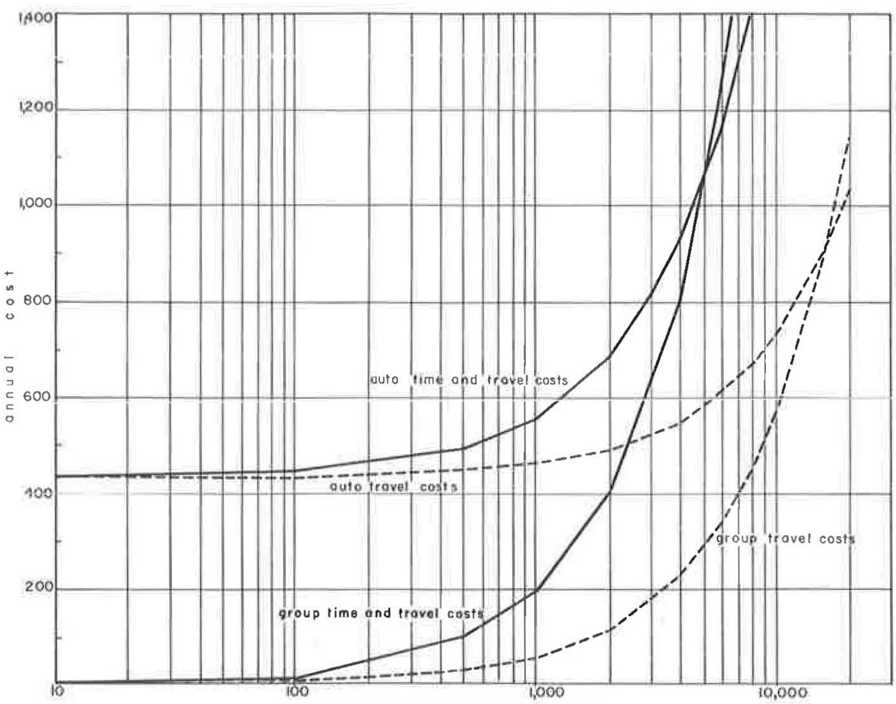

Figure 3. Comparison of annual travel and time costs for individual and group transportation as a function of miles traveled per year.

year. This is because the automobile owner must start from the higher level of fixed investment in a vehicle.

If this is an accurate appraisal (and the figures appear reasonable), then fewer people would use their cars than now do. However, if it is assumed that person time has an average value of $1.00 per hour, then the costs of group transportation use rise to intersect the costs of automobile use at a point where about 6,000 mi of travel per year are undertaken. This is equivalent to a round trip to work and back of 12.5 mi each weekday (five-day week).

Appraising Figure 3, then, one would observe that for those persons who travel less than 6,000 mi per year, group transportation is undoubtedly the less expensive. For those who travel more than 6,000 mi per year, individual transportation is less expensive. Generally, persons with lower incomes live in the older and denser portions of cities; they cannot afford to travel much and their needs are more apt to be met close at hand. Group transportation is much more economical for them. For the suburban family, income and travel distances are greater; individual transportation is a better bargain.

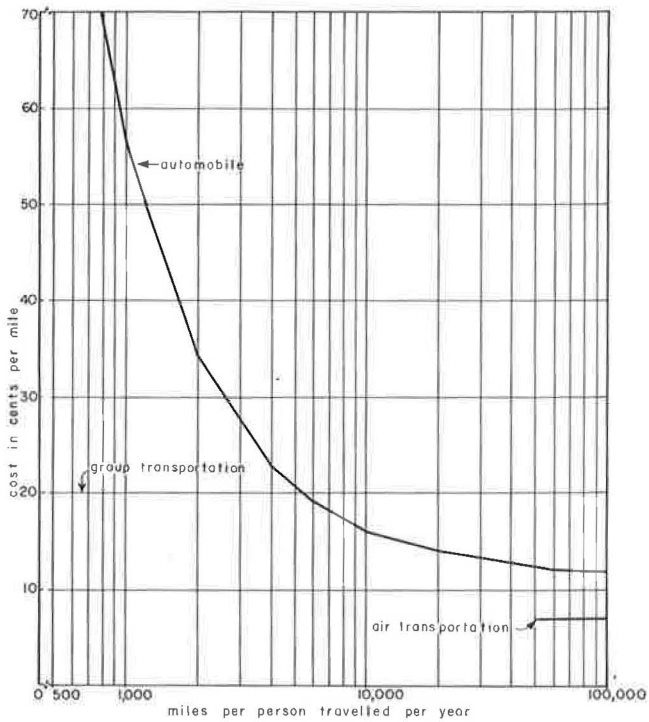

Figure 4. Comparison of time and movement costs per mile and number of miles traveled by mode of travel.

Figure 4 shows the same data as in Figure 3, but on a cost-per-mile instead of on an annual cost basis. This shows clearly how, with increasing use, individual transportation becomes progressively less expensive to the user. The positions of the lines shown here may vary, but the principle remains the same. As an afterthought, the cost of air travel is shown for the persons who travel more than 50,000 mi per year. At $0.07 per mile and with little time cost ($1.00 divided by 250 mph is less than a $0.01 of time per mile) air travel is quite inexpensive when a great deal of traveling must be done.

Summary

In this part, the choice of transportation mode has been analyzed from the viewpoint of the user, who is assumed to be an economic man with good knowledge of alternative costs.

An analysis of movement costs suggests that the user considers other things besides movement costs in making a choice. If his viewpoint were solely movement costs he would walk for all journeys. Automobile costs would appear to be a high cost form of transportation. Bus travel would be economical for long journeys.

A hypothesis was advanced that time costs (as appraised by the traveler) vary with the amount of travel (in time) per day. This hypothesis is reasonable, but lacking evidence, time costs are considered on a fixed average basis in later parts of this paper.

Using a fixed value of time, choice of mode can be graphed, including both time and movement costs, on an annual basis. This kind of presentation suggests that choice of mode is a function of the amount of travel purchased per year by the consumer. Those who purchase very little travel will tend to use group transportation. Those who purchase more travel will tend to use individual transportation.

SELECTION OF CAPITAL INVESTMENT POLICY

Selection of a capital investment policy for transportation systems is a critical problem in urban planning, and hence to metropolitan management. The following analysis is focused mainly on the problem of optimizing investment for two modes of transportation—individual and group. Actually, this could be considered as a four-mode problem, because the authors deal with travel on buses, rail rapid transit, arterials, and expressways. However, the investment is only in two modes (rails and expressways).

Much has been written about "balanced" transportation systems. What is or what is not balanced has never been decided and rarely is defined. It might be defined from the viewpoint of metropolitan management as the proportion of persons traveling by individual and group transportation at the point where total transportation costs are least. However, the proportion which is least cost now may very well not be at least cost twenty years from now. Thus the idea of "balance," with its implications of a static situation over time, may be misleading. The problem of the amount and timing of investment is probably more important.

In order to select—or perhaps more properly to move toward—an optimum capital investment policy, a system must be created for determining what is optimum. This system requires both a criterion for selection, and a basis for making the necessary calculations or approximations.

The criterion has already been established: from the viewpoint of metropolitan management, the goal is to minimize the sum of all transportation costs. Hence this part opens with a discussion of systems for calculating optimum points, or, more accurately, for arraying alternative costs.

Systems for Calculation of Alternative Investment Costs

There seem to be four substantially different methods of calculating alternative investment costs. These include (a) the method of comparing alternative single routes, (b) the method of equal percentage returns, (c) the method of economic evaluation of traffic assignments, and (d) the method of simplified models. These are discussed in turn.

Method of Comparing Alternative Single Routes.—A conventional method of studying alternative costs is to compare the costs of single routes. One route may be compared with another, or with the option of not building it at all. Very detailed accounts have been suggested with this type of work (7, p. 34).

There are two difficulties with this method: (a) the great volume of detailed work, which may be of misleading accuracy, and (b) the fact that a system is not being dealt with (7, p. 95). It is quite possible for a single road or rail line to be unprofitable in itself but to increase profits for a whole system.

Method of Equal Percentage Returns.—Basically, the method of equal percentage returns distributes available investment capital among alternatives on the basis of the marginal rate of return. If two or more activities are independent, the optimum investment policy is one which equates the rate of return on the increments of investment in the several activities.

This holds true as long as there is no, or extremely little, connection between the activities. In simplest form, without budget constraints or an existing physical plant, this is a cumulation of individual maxima for each activity. In a somewhat more realistic framework this approach allocates investment among alternatives subject to budget limitations. For example, if there were no connection between group and individual transportation and an investment in transportation were to be made, the optimum investment would be that split which yielded an equal return on the additional investment in each mode.

There is some evidence for holding that group and individual transportation are independent—at least for crude levels of precision. Keefer (8) has shown that very high percentages (85 percent in Pittsburgh) of transit users are "captives." The other side of the question—how many automobile drivers and passengers are actual "captives" of their mode—has not been answered. Without further evidence of even a crude independence of mode the equal rate of return approach is difficult and dangerous to use for this problem. The "lumpiness" of efficient investment units between several facilities also makes this approach difficult.

In other areas of metropolitan management concern, where a comprehensive and detailed accounting is impossible, this approach provides a useful yardstick. For example, this is the only feasible way, at present, for evaluating investment policy in transportation against investment policy in land development or hospitals or public open space.

Method of Economic Evaluation of Traffic Assignments.—Traffic assignments currently in use in various transportation studies offer what is probably the most trustworthy means of measuring all costs (that is, all transportation costs) associated with a particular transportation system plan, including both road and transit systems. These methods can estimate the traffic volumes on each link of both road and group transportation systems. Because traffic volumes, coupled with information on road or bus system characteristics, determine time, accident, and vehicle operating costs, it is quite easy to sum up the total costs, including construction costs, for each system plan.

Such a method of accounting, completely computerized, is far superior to the system of comparing alternative single routes. It automatically takes into account the reduced costs which occur when persons use low-cost systems (for example, rail rapid transit or expressways) instead of the higher-cost bus and arterial systems. The increased capital requirements also are taken into account.

One problem with this method—and it may be more theoretical than real—is that because of the time and cost of running computer traffic assignments, not all possible systems may be tested. Hence, there may be one which is superior to all tested solutions. In reality, of course, the severe limitations which restrict the number of possible schemes make it unlikely that a substantially better plan will have been missed.

Method of Simplified Models.—Because the preceding method is long and cumbersome, it is desirable to have another method for two reasons. One is to organize the important constituent determinants of an optimum investment policy so that the principles of optimization are understood. The second is to have a method that can be used in planning—that will permit plans to be prepared which are close to the optimum, so that a smaller range of plans can be tested. More tests on fewer plans presumably would provide greater precision.

Naturally, these models require simplifications and abstractions from the complexities of the real world. There is no harm in this, provided the models are thoroughly understood both in derivation and in purpose.

Several of these models already exist. One is the optimum spacing model, which treats the problem of optimizing investment in expressways in an all-road situation (9, 10). Another model deals with the optimum location of transfer stations in an all-rail problem (11).

Problems which have not been treated include the optimization of subway construction in a sector of varying density, and the problem of the optimization of the mix of road and rail transit improvements. These are examined in the following two sections of this paper.

A Model for Optimizing Rapid Transit

This section of the paper is an off-shoot from the main argument, in the sense that it is not concerned with both group and individual transportation, but is limited to group transportation. Nevertheless, the problem dealt with here is a complex one of great interest. Its solution should be extremely useful, not only in its present elementary form but also as a base for further refinement and possibly for extension to include both group and automobile transportation.

A question in cities having no form of rail rapid transit is whether to build such a rapid transit line, and if so, how long a line should be built. Assuming that rapid transit should pass through the central business district (CBD), the problem can be stated: how far out should a rapid transit line be built from the CBD? This section presents a mathematical solution to this problem.

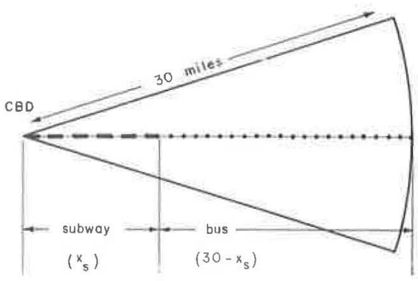

Figure 5.

Assume a sector of the city radiating out from the CBD a maximum distance of 30 mi. This sector is populated with people at a density which declines as distance from the CBD increases. Assume that all these people (or it could be a proportion, either constant or varying) travel to the CBD by bus. Because the angle of the sector is known, this population of bus riders can be considered either as living throughout the sector or as living on a single line—the bus line (see Fig. 5).

Let it be taken, then, that all bus riders live along a bus line, but at a decreasing density from the CBD in accordance with

$$\text{density} = a\, e^{-x/K} \tag{1}$$

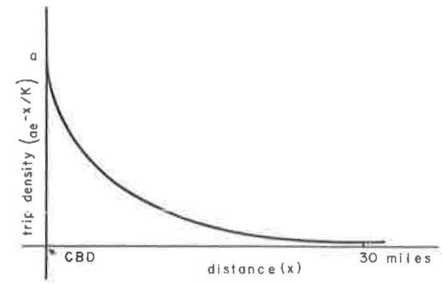

Figure 6.

in which x is distance from the CBD and a and K are constants. This can be graphed as shown in Figure 6.

The problem can now be stated: how far out (x_s) should a subway be built from the CBD in order to minimize the sum of travel and construction costs? For simplicity, let it be assumed that all persons travel each day to the CBD by bus, and that wherever they meet the end of the subway line they will transfer, without time loss, to the subway and proceed on the subway. Their reason for transferring is because subway travel is cheaper in time and operating costs than is bus travel. The mathematical statement of this problem follows (12).

For any values of x, say x_i and x_j with $x_i \le x_j$, $\int_{x_i}^{x_j} a\, e^{-x/K}\, dx$ represents the total number of trips originating within the range $x_i \le x \le x_j$, whereas, $\int_{x_i}^{x_j} a\, x\, e^{-x/K}\, dx$ represents the total person-miles of travel resulting from these trips. Now, because all trips with origins in the range $o \le x \le x_s$ (x_s is length of subway) use the subway exclusively for a distance of x miles, and all trips with origins in the range $x_s < x \le 30$ use the subway for x_s miles and use the bus for $(x - x_s)$ miles, the following equation may be developed to sum the costs of travel and subway construction:

$$\text{Total cost} = C_3\, x_s + C_1 \left[\int_o^{x_s} a\, x\, e^{-x/K}\, dx + x_s \int_{x_s}^{30} a\, e^{-x/K} dx \right] +$$

$$C_2 \left[\int_{x_s}^{30} a\, x\, e^{-x/K}\, dx - x_s \int_{x_s}^{30} a\, e^{-x/K}\, dx \right] \tag{2}$$

in which C_3 is the construction cost of subway travel, in dollars per mile, converted to a daily basis; C_2 is bus travel costs, in dollars per mile; and C_1 is subway travel costs, in dollars per mile.

In word form, Eq. 2 says that the total costs of transportation in the sector of the city under study are equal to the construction cost of the subway plus the cost of all person-miles of travel on subways plus the cost of all person-miles of travel on buses. To minimize total costs, Eq. 2 is first integrated, then differentiated with respect to x_s, equated to zero, and solved for x_s. The resulting value of subway length is

$$x_s = -K \ln\left[e^{-30/K} - \frac{C_3}{(C_1 - C_2)\, a\, K} \right] \quad (3)$$

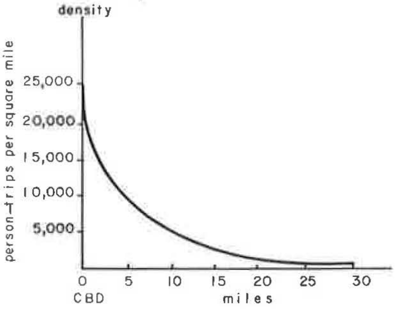

Figure 7.

in which ln is the natural logarithm function.
Now it can be shown that this value of x_s minimizes total cost if, and only if, $C_1 < C_2$. This condition is reasonable because bus travel costs are greater than subway travel costs.

Eq. 3 reveals some interesting and reasonable properties with respect to the unit costs involved, as follows:

1. The length of subway will decrease if construction costs rise.
2. If bus travel costs rise (as by increased operating costs or slower speeds), more miles of subway should be built.
3. If subway costs decrease (as by lowered operating costs or higher speeds), more miles of subway should be built.

Some sample results are now in order. For a = 25,000 person-trips per square mile per day and K = 6, the density relation takes the particular form

$$\text{density} = 25{,}000\ e^{-x/K}, \quad 0 \le x \le 30 \quad (4)$$

which has the form shown in Figure 7 and which is assumed to approximate reality. The rate of decline of the curve can be varied by changing the value of K; this adds to the flexibility of Eq. 3 and, therefore, to its usefulness in finding solutions for different sets of empirical data. Also, assuming C_1 = \$0.12 per mile (subway travel, including time cost), C_2 = \$0.19 per mile (bus travel, including time cost), and C_3 = \$1,500 per mile (subway construction cost per day), Eq. 3 gives $x_s = -6 \ln [e^{-5} - 1{,}500/(-0.07 \times 150{,}000)]$, or x_s = 11.4 mi.

Because the input figures do not pertain to any particular city, the distance value given for x_s in this example should not be considered as being an actual value.

The value of this work is that it provides a simple means for estimating the optimum length of subway construction as a function of trip density, bus travel costs, subway travel costs, and construction costs. The trip density curve, being a declining function, approximates the actual declines in urban densities.

Optimizing Investment in a Two-Mode Transportation System

In previous sections, ideas have been presented on the goals of travelers and of metropolitan management, and on the choice of transportation from the traveler's viewpoint. Various methods have also been described for estimating optimum investments in transportation systems, including the method of evaluating individual facilities, the method of equal percentage returns, the method of assignments, and the method of simplified models.

In this section, a simplified model is presented which may be used for studying travel and capital costs associated with different investment combinations of improved individual and group transportation facilities. This section attempts to provide a means for answering questions such as: How much should be invested in expressways?; How much should be invested in rail rapid transit?; and What is the best combination of investments?

An understanding of the relationship between alternative costs should be extremely helpful in planning transportation systems for urban areas. A secondary purpose of this section is to lay the groundwork for computer programs which may consider more complicated situations than here developed. A third purpose is to lay the groundwork for developing a formula for finding the optimum point, or points, for capital investment in group and individual modes of transportation.

In this section, the basic unit dealt with is the person-mile of travel (PMT), which is a small enough unit so that it can be dealt with in continuous terms. The cost of person-miles of travel on different types of facilities is known fairly well. Furthermore, it is possible to estimate reasonably well how PMT will be allocated to different types of facilities as a function of the amount (or spacing) of these facilities. Because the amount (or spacing) of facilities is a direct function of investment, it is thus possible to relate travel costs to investments, and hence to know total costs. Use of the PMT unit avoids the substantial difficulties inherent in dealing with trips as a basic unit.

Throughout this section, the unit of area dealt with is a 1-sq mi section of urban territory, the same assumption used in other "simplified model" solutions described herein. The basic assumption of the unit square mile is that a large urban area of identical density, trip length, transportation facilities, etc., surrounds the square mile under consideration. It is necessary to make this assumption in order to construct the kind of model herein described.

To permit a more rapid presentation of the subject the various variables employed are described as follows:

G = proportion of travel made by group transportation;
X = proportion of individual transportation on expressways;
R = proportion of group transportation on rail rapid transit facilities;
O_A, O_B, O_X, O_R = the respective PMT (operating and time) costs on arterials, buses, expressways, and rail rapid transit, in $0.01 per mile of person travel;
C_X, C_R = construction costs of expressways and rail rapid transit facilities expressed in daily terms;
T = sum of operating costs plus construction costs;
z_1, z_2, z_3 = spacings of expressways, arterials and local streets, respectively;
ρ = trip density, in person-trip destinations per square mile;
$\bar{r}$ = mean trip length;
y_1, y_2 = spacing of rail rapid transit lines and bus lines, respectively; and
V_X, V_R = volumes of persons per day passing points on expressways and rail rapid transit lines, respectively.

Consider plane ABCD in Figure 8. On this plane the horizontal axis represents the percentage, X, of person-miles of travel (PMT) driven on expressways. At point $X = 0.0$, all person-miles of travel are placed on arterial or local streets. The vertical axis represents O, or the cost of PMT, a joint function of vehicle operating costs (including depreciation) and time costs. The PMT cost declines from O_A to O_X as larger percentages of PMT are placed on expressways, because expressway travel is faster and safer, with less wear and tear occasioned by stop and go driving. The decline is a linear relationship.

Consider also plane EFGH in Figure 9. On this plane the horizontal axis represents the percentage, R, of PMT placed on rapid transit (subway, elevated, and/or monorail, but not express buses). At point $R = 0.0$, all person-miles of travel are placed on bus systems. The vertical axis represents the cost of PMT, a joint function of fares and time costs. Fares are assumed to cover all operating costs (including vehicle depreciation, labor, fuel, oil, and tire costs) but not to cover any capital costs, whether of roads or of rails, stations, or other capital expenditures.

The PMT cost declines from O_B to O_R as larger percentages of PMT are placed on rail rapid transit. This is primarily because rail rapid transit travel is faster and safer. The decline is a straight-line relationship.

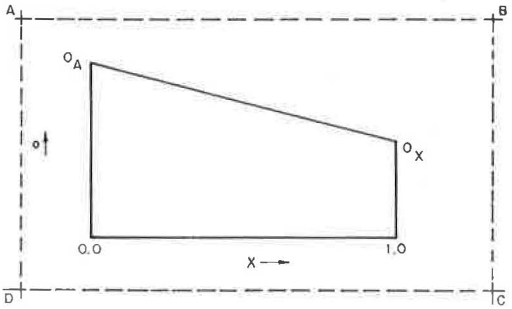

Figure 8.

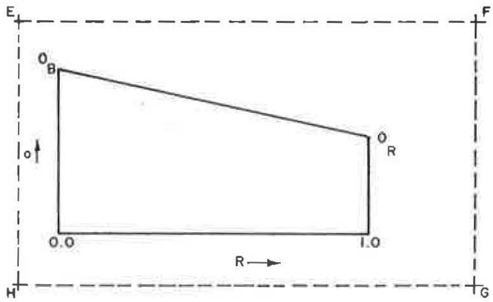

Figure 9.

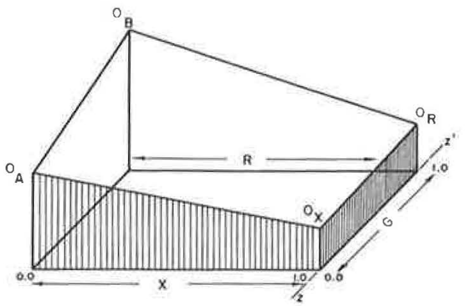

Figure 10. Surface of operating costs (X = R).

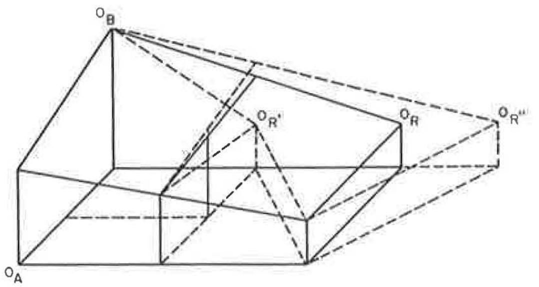

Figure 11. Surface of operating costs (variable R).

In both cases, PMT is expressed as an average cost per mile of travel. This assumption is necessary in dealing with group transportation, because fixed fares produce variable per-mile costs as a function of trip length.

The two planes, ABCD and EFGH, are now placed parallel to each other and at a distance apart on the z axis, which is scaled in units of G; G is 0.0 where intersected by plane ABCD and 1.0 where intersected by plane EFGH. This is shown in Figure 10, from which it is possible to consider the surface of person-miles of travel cost. This surface, identified as $O_B O_R O_X O_A$, gives the person-miles of travel costs for any combination of G and X, but only where X = R.

Inasmuch as the preceding assumption about the equality of R and X is rarely likely to be true, it is necessary to develop a procedure for graphically measuring the costs when R is not equal to X. This is done by simply lengthening or foreshortening the scale on which R is measured so that any value of R can be placed directly opposite any value of X. By this device, as illustrated in Figure 11, the unit costs for any combination of G, X, and R can be calculated.

Obviously, graphical devices are limited in their usefulness for making calculations, although they are very useful in conveying ideas. Hence it is necessary to develop a formula which will express unit costs of transportation for any combination of G, R, and X, as follows:

$$\text{Operating and Time Cost} = \bar{r}\,\rho\, G\,[(1-R)\,O_B + R\,O_R] + \bar{r}\,\rho\,(1-G)\,[(1-X)\,O_A + X\,O_X] \quad (5)$$

In a city where there are no expressways and no rapid transit lines, all persons would have to travel on arterial streets, either in buses or in individual vehicles. Costs would then be expressed by a simplified version of Eq. 5, as follows:

$$\text{Operating and Time Costs} = \rho \bar{r} G O_B + \rho \bar{r} (1 - G) O_A \qquad (6)$$

If metropolitan management decides to provide expressway and rail service in the square mile under consideration, some of the residents' PMT will be allocated to the higher type facilities. The proportion, X, of individual PMT allocated to expressways can be calculated from

$$X = \frac{1}{z_1 \left[\frac{1}{z_1} + \frac{1}{\bar{r}} + \frac{z_2}{\bar{r}(z_1 - z_3)} \right]} \qquad (7)$$

which is adapted from Schneider's (13) "direct assignment" formula. Similarly, the proportion, R, or percentage of PMT on rail facilities can be calculated from

$$R = \frac{1}{y_1 \left(\frac{1}{y_1} + \frac{1}{\bar{r}} \right)} \qquad (8)$$

which is a simplified version of Schneider's formula for a two-mode (bus and rail) system.

However, metropolitan management is conscious of capital investment costs required to permit people to move faster and more safely. These costs are determined by

TABLE 2

TOTAL DAILY COSTS FOR SELECTED PROPORTIONS OF GROUP AND INDIVIDUAL TRANSPORTATION AT VARYING SPACINGS FOR EXPRESSWAYS AND RAIL TRANSIT[1]

(Trip Density = 10,000, Mean Trip Length = 6 Miles)

Using Group Trans. (%)	Spacing (mi)		Person-Vol./Mi (1,000's)		PMT (%)		Total Daily Costs ($)
	Exp.	Rail	Exp.	Rail	Exp.	Rail	
0	10	None	106	None	36	0	10,206
	5	None	75	None	49	0	9,580
	3	None	54	None	59	0	9,270
	2	None	40	None	67	0	9,560
25	10	3	80	15	36	67	11,002
	5	5	56	21	49	56	10,720
	3	3	40	15	59	67	10,510
	2	5	30	21	67	56	10,800
50	10	3	53	30	36	67	11,382
	5	3	38	30	49	67	11,270
	3	3	27	30	59	67	11,360
	2	3	20	30	67	67	11,650
75	10	3	26	45	36	67	11,692
	5	3	19	45	49	67	11,780
	3	3	14	45	59	67	12,030
	2	3	10	45	67	67	12,400
100	None	10	None	112	0	36	13,376
	None	5	None	82	0	56	12,150
	None	3	None	60	0	67	11,690
	None	2	None	45	0	73	11,680
	None	1	None	26	0	83	11,560

[1] Rail transit spacings, Y_1, of 10, 5, 3, 2, and 1 mi used for each expressway spacing. Only the minimum total cost rail spacings are shown where both group and individual modes of transportation are used.

The following values are assumed in the calculations:

Trip density, ρ = 10,000
Mean trip length, $\bar{r}$ = 6 mi
Arterial autos, O_A = \$0.20/mi
Expressway autos O_X = \$0.10/mi
Rail transit, O_R = \$0.15/mi
Buses, O_B = \$0.26/mi
Arterial spacing, z_2 = 1 mi
Local street spacing, z_3 = 0.1 mi
Expressway spacing, z_1 = as indicated
Capital costs at 8% interest, 25 years for recovery. Expressways are \$1,460 per day or \$5 million per mile. Rail at \$880 per day or \$3 million per mile.

$$\text{Expressway investment} = \frac{2\,C_X}{z_1} \qquad (9)$$

$$\text{Rail rapid transit investment} = \frac{2\,C_R}{Y_1} \qquad (10)$$

$$\text{Total investment} = 2\left(\frac{C_X}{z_1} + \frac{C_R}{Y_1}\right) \qquad (11)$$

Two examples have been studied. In the first, a medium density area is investigated—one which has a trip population of 10,000 trips per square mile, equivalent to about 5,000 persons per square mile (Table 2). This is a solidly built-up suburban settlement. The ratio of bus:rapid transit:arterial auto:expressway auto costs was taken as 26:15:20:10. This means that the individual travel costs were lower than group costs by about one-third, whereas express travel costs (either expressway or rail rapid transit) were considered about one-half of those on unimproved facilities. These are conservative estimates. Again, the figures given here are subordinate to the principles and methods.

TABLE 3

TOTAL DAILY COSTS FOR SELECTED PROPORTIONS OF GROUP AND INDIVIDUAL TRANSPORTATION AT VARYING SPACINGS FOR EXPRESSWAYS AND RAIL TRANSIT[1]

(Trip Density = 50,000, Mean Trip Length = 6 Miles)

Using Group Trans. (%)	Spacing (mi)		Person-Vol./Mi (1,000's)		PMT (%)		Total Daily Costs ($)
	Exp.	Rail	Exp.	Rail	Exp.	Rail	
0	10	None	545	None	36	0	67,171
	5	None	391	None	52	0	60,542
	3	None	284	None	63	0	56,705
	2	None	211	None	70	0	55,055
	1	None	119	None	79	0	56,410
25	10	3	409	75	36	67	66,649
	5	3	293	75	52	67	61,970
	3	3	213	75	63	67	59,483
	2	3	158	75	70	67	58,733
	1	3	89	75	79	67	61,213
50	10	2	273	112	36	75	63,799
	5	2	195	112	52	75	61,070
	3	2	142	112	63	75	59,993
	2	2	106	112	70	75	60,083
	1	2	60	112	79	75	63,688
75	10	1	136	96	36	86	60,607
	5	2	98	169	52	75	59,870
	3	2	71	169	63	75	60,083
	2	2	53	169	70	75	61,133
	1	2	30	169	79	75	65,863
100	None	10	None	562	0	38	66,286
	None	5	None	409	0	54	61,171
	None	3	None	300	0	67	58,053
	None	2	None	225	0	75	56,328
	None	1	None	129	0	86	55,656

[1] Rail transit spacings, Y_1, of 10, 5, 3, 2, and 1 mi used for each expressway spacing. Only the minimum total cost rail spacings are shown where both group and individual modes of transportation are used.

The following values are assumed in the calculations:

Trip density, ρ = 50,000
Mean trip length, $\bar{r}$ = 6 mi
Arterial autos, O_A = \$0.28/mi
Expressway autos, O_X = \$0.115/mi
Rail transit, O_R = \$0.15/mi
Buses, O_B = \$0.26/mi
Arterial spacing, z_2 = 0.5 mi
Local street spacing, z_3 = 0.1 mi
Expressway spacing, z_1 = as indicated
Capital costs at 8% interest, 25 years for recovery. Expressways are \$5,855 per day or \$20 million per mile. Rail at \$2,928 per day or \$10 million per mile.

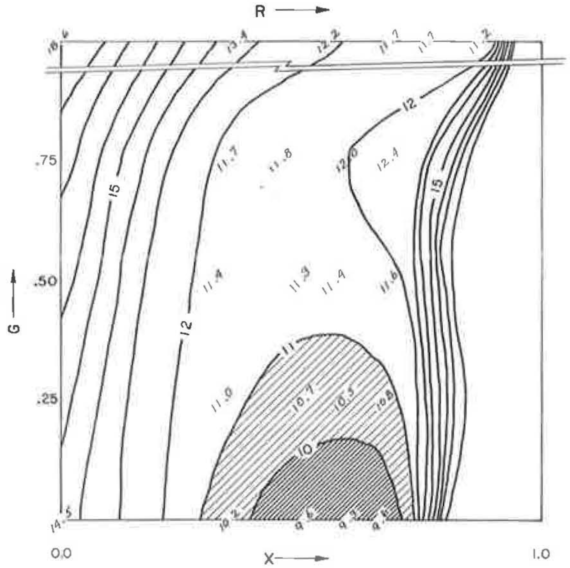

Figure 12. Cost surface for Example 1. (Data plots where G < 0.75 are with respect to X.)

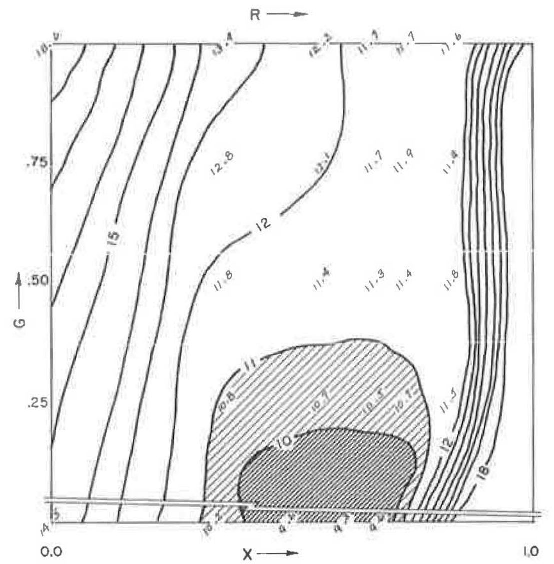

Figure 13. Cost surface for Example 1. (Data plots where G ≥ 0.25 are with respect to R.)

In Figures 12 and 13 the resulting costs surfaces are shown by the use of the isoline or contour technique. A word is necessary on the construction of these figures. Inasmuch as four variables are being presented (T, G, R, and X) it is obvious that one variable cannot be shown, except in the case where one of the other variables is zero. In Figure 12, the missing variable is R, which is not shown except along the line G = 1.0. Therefore, in each plot, for any particular value of G and X, the minimum T value is plotted as determined by one or another of the values of R. The mate of Figure 12 is Figure 13, in which the X values disappear, except along the X-axis.

Both Figures 12 and 13 show that the minimum cost point is associated with optimum investment in expressways. Investment in rail rapid transit facilities would produce some gains, but not nearly as fast as investment in expressways. There is a lightly-defined minimum point in the all group world, but it is substantially more costly than the minimum point in the all individual transportation solution.

In contrast, a very high density area was selected as the second example. A trip density of 50,000 person-trips per day per square mile was chosen, equivalent to about 25,000 persons per square mile (Table 3). In this example, the ratio of bus:rapid transit:arterial auto:expressway travel costs was taken as $26{:}15{:}28{:}11\frac{1}{2}$. This means that automobile travel on arterial streets was set higher than bus costs. This is conceivable if congestion and parking fees are high enough.

The result, as shown in Figures 14 and 15, is to produce a definite, two-minimum solution. Either an all expressway or an all group transportation solution would produce minimum costs of about \$55,000 per day per square mile. However, it must be remembered that the costs of constructing facilities were not forced up as a function of increased volume usage. Probably the costs of expressways would rise faster than those of rail rapid transit facilities at this density; the inclusion of these costs might show a clear minimum in the group transportation world.

With such cost surfaces placed in front of metropolitan management, the direction and timing of investment can be studied with much greater facility than otherwise. For most cities, with medium to low densities, and with G values of about 0.25 or less, the direction of investment will probably be toward the expressway solution. For high-density cities, where G > 0.5 it may be more desirable to move toward the all-transit solution. Compromising by trying to maintain a dual policy is probably the most expensive policy.

Density plays an extremely important part in determining costs—not directly, because the quantity ρ does not appear in the equations fixing the proportionate usage on expressway or rail lines, but indirectly in determining costs of construction and speed of travel.

These observations appear reasonable, but must be treated with some caution. One of the reasons for caution is that the foregoing calculations have not varied costs of construction, costs of travel, or speeds as functions of the volumes of persons using each type of facility. Such changes might change the cost surfaces. Second, the model is based on the necessary assumption of a unit square mile. This assumption has obvious limitations. Third, the assumption of a gridded rail transit network is weak; different formulas governing allocation of group PMT to rail rapid transit should perhaps be developed.

Nevertheless, these known difficulties do not detract from the basically simple method of cost surfaces which has been presented here. It will be seen that this method can readily be extended and made more "realistic" by programing it for a computer. The calculations necessary to produce Tables 2 and 3 took about two man-days; a computer could produce more complete answers in minutes. A computer program could take into account:

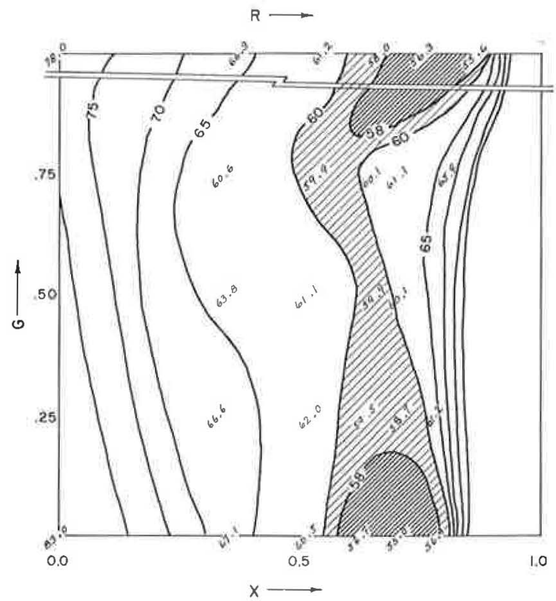

Figure 14. Cost surface for Example 2. (Data plots where G < 0.75 are with respect to X.)

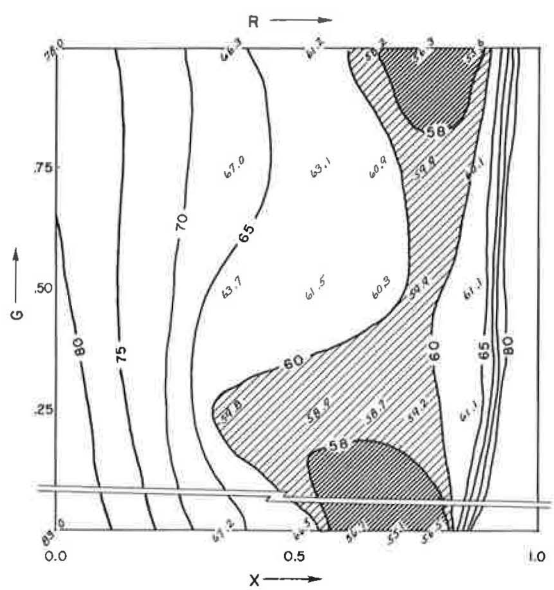

Figure 15. Cost surface for Example 2. (Data plots where G ≥ 0.25 are with respect to R.)

1. Travel costs (time, accidents, and operating costs) as direct functions of volumes on each type.

2. Different capital costs as a function of volumes on each type of road or group transit facility.
3. Capital costs as functions of population density.
4. Variable fares.
5. Increased capital costs of rapid transit facilities if fares do not cover operating costs; reduced capital costs if fares more than cover operating costs.

SUMMARY AND CONCLUSIONS

This paper was triggered by the question of congestion tolls, but has been focused on the problem of investment in transportation systems of various types. There are two main reasons for this change in focus. First, congestion toll accounting does not take the supply of facilities into account; it is static in outlook, hence is an inadequate framework for planning. Second, it does not deal with the questions of mode of travel or of toll roads where tolls were imposed for reasons of financing.

An attempt has been made to provide a framework for making investment decisions across the board for both individual and group modes of transporting people within urban areas. The viewpoint taken is that of metropolitan management, a hypothetical person or group concerned with urban affairs.

To make investment decisions, metropolitan management must establish an accounting system and it must understand how people will behave when given certain choices. The proposed accounting system includes people's travel costs by mode, and metropolitan management's costs in supplying new transportation facilities. The rule is that the accounting system shall be as inclusive as possible. The goals of site users and non-transportation goals of metropolitan management are examined; but present knowledge, lack of theory, and data limitations prevent their inclusion within the accounting framework. Hence metropolitan management accounts, basically, for personal time, accident costs, vehicle operating costs, and capital (construction and right-of-way) costs in deciding how it should best invest in transportation.

The behavior of people was studied briefly. It is assumed that people are selfish in their choice of mode and that their personal time is of real value to them because its supply is fixed. Choice of mode is clearly not made with respect to movement costs alone; time does have value. A long-term view of alternative transportation costs suggests that the amount of travel consumed annually is important in determining mode of travel. When less than 6,000 to 7,000 miles of travel are undertaken per person each year, group transportation is less expensive. When more than 6,000 to 7,000 miles are traveled, individual travel is less expensive.

To set up a decision framework, all costs were cast in terms of person-miles of travel. Such a unit is needed to make valid cross-comparisons between modes. A model was developed based on a unit square mile of urban terrain.

First, cost surfaces were developed for travel costs (time, accident, and operating costs) as functions of the proportions of PMT allocated to group transportation, G, and to expressways, X, and rail rapid transit, R. The rules for the allocation of automobile PMT to expressways, X, and for the allocation of bus PMT to rail rapid transit, R, were fixed by formula, as functions of expressway and rail rapid transit spacing. The formula assumes that people will allocate PMT to higher-speed facilities if they are present. No formula for allocation of PMT to the group or non-group modes, G, was used; instead, costs associated with many values of, G, were studied.

Second, capital costs were calculated for various values of G, R, and X, and a total cost surface was created. Two examples show how these surfaces appear in medium- and high-density situations.

Given these surfaces, some tentative answers can be provided to three questions raised earlier: (1) What total investment should be made in transportation facilities? (2) What types of facilities should be invested in and how much of each? (3) What role should subsidy or tolls play in the transportation system? There are two further questions of equal importance which are not directly answered here: (4) What should be the timing of investment? (5) Where in the region should the investment be made?

What Total Investment Should Be Made in Transportation Facilities?

Ideally, investment in transportation should be made up to the point where the return on transportation investment is equal to the return on all other metropolitan investments. This would achieve metropolitan management's goal of optimum allocation of resources. But this requires cross-comparisons of such different community investments as transportation and public health, and there is not yet capability for fully evaluating or equating the consequences of different investments in these areas.

Instead, one must be content with guaranteeing achievement of a prior and less inclusive goal—to minimize total transportation costs. The inclusion of an adequate interest rate (7 to 10 percent) within the minimization cost framework is desirable. Having this kind of return on investment provides assurance against over-investing in the transportation sector.

The answer to the first question, then, is that in the absence of criteria and procedures to determine and compare the relative community benefit from investment in alternate sectors of the public economy, the transportation investment goal is to move toward a minimization of total transportation costs—both travel and investment costs.

What Types of Transportation Facilities Should Be Invested in and How Much of Each?

There are really two questions involved in this section. These are: (1) What is the modal split likely to be? and (2) What express facilities should be built for each mode —that is, individual and group transportation? These are difficult questions, but answering them is facilitated by reference to the diagrams of transportation cost surfaces shown in Figures 8-15.

Modal Split.—First, choice of mode appears to be a function of the amount of transportation being purchased by the consumer and of the relative cost to him of alternative modes. Many people purchase so little transportation that mass transportation is always more economical, as shown in Figure 3. Others, by reason of age or disability, cannot drive. But for most people, enough transportation is purchased so that they become discriminating. For these people, relative transportation costs affect their allocation of their PMT to one or another system.

Relative costs are composed of movement costs (fares, vehicle operation, accidents, depreciation, etc.) and time costs. Relative cost between individual and group modes of travel may vary substantially on a per-mile basis. In medium- to low-density areas, individual modes of transportation generally are cheaper—that is, the plane of travel costs is tilted down toward the individual transportation. However, in very high-density areas, the group modes may be substantially equal to or even lower in cost than the individual transportation modes.

Those who purchase enough transportation to be discriminating will probably select mode on the basis of relative cost. How these persons will apportion their PMT, on the average, between group and individual transportation is not known. (Probably formulas will be developed shortly which will make the estimation of mode choice easier, just as Schneider's direct assignment formula (13) makes possible the estimation of allocation of PMT between arterials and expressways.) One can, however, study the relative costs, as was done herein, then assume that, over time, people will generally move toward the lower cost portion of the surface. In any event, it is possible to array the costs as a function of all values of G. Knowing the present value of G, it is possible to estimate what changes will be made and in what direction to invest.

What Express Facilities Should Be Built for Each Mode?—The amount of express facilities which should be built for each mode can be calculated separately for each mode. This is simply the optimum spacing problem. A special solution for rail rapid transit, not using the unit square mile approach, was also given herein.

The question of the proper combination of investments is more difficult, but some things can be inferred from a study of the surfaces presented in this paper. The inferences must be treated with caution because of the limited number of examples studied and for the other reasons cited previously.

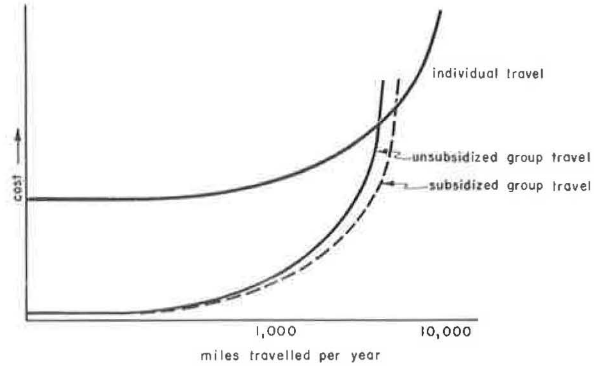

Figure 16.

(a) Initial investment in rail facilities, expressways, or any combination of these facilities will almost always produce some gain. The reason for this is that investment cost, when placed on a daily basis, is a small proportion (10 to 20 percent) of total daily travel costs, yet it will cause substantial reductions in daily travel costs.

(b) Exclusive investment in expressway or rail rapid transit would appear to produce greater gains than a combination of these two types.

(c) Combination investments generally appear to be more expensive because the capital requirements are high and full utilization of each type can not be expected.

(d) The direction in which investments should be made can be seen by determining where on the surface of total cost a particular area is at present. If the proportion of mode split of PMT is less than 0.5, the more economical investment pattern would probably be toward expressways, where the ultimate minimum costs will probably be least. If the proportion of PMT on group modes is greater than 0.5, serious consideration should be given to an all-rail investment pattern.

What Role Should Subsidy or Tolls Play?

Subsidies and tolls are basically means of affecting choice of mode or route of travel. They are actually points along a continuum of encouragement, neutrality, and discouragement. The authors consider subsidies and tolls only from this viewpoint, and not from the unnecessarily strict viewpoint of requiring a tax or payment for every increment of benefit which is conferred on people. A great deal of confusion arises from too strict an interpretation of use taxation. It would be ridiculous, for example, to require all liquor taxes to be devoted to curing alcoholics.

As control devices, either subsidies or tolls are weak because they affect only a minority of travel costs—that is, the movement portion of the costs. The larger proportion—time costs—is therefore still decisive. Inasmuch as tolls take effect as a function of a person's value of time, and time value probably is mainly a function of income, tolls are highly discriminatory, income-wise. The most effective encouragement or discouragement is not subsidy or toll, but relative changes in speed and safety.

Subsidies are generally discussed only in the group transportation world. The effect of subsidies, illustrated by Figure 16, is simply to reduce the apparent cost to the user, and thus to increase the amount of annual travel within which group transportation is considered less costly. Whether this is worth it or not is not known; much would depend on density and on income level. Furthermore, the effect of a subsidy may not be great, because, as already mentioned, it only affects the movement portion of the costs.

Tolls can be considered in two groups. In one group are the tolls imposed on roads as devices for providing financing when other financial means are not available. Major tollways conceived prior to the 1956 Highway Act fall in this category. These facilities provide service to those who wish to select it far ahead of the time when such roads would otherwise be built. Lives are saved which otherwise would have been lost, and those who use these roads confer benefits not only on themselves but also on those who do not use them. However, tollways within urban areas do create definite problems which would not exist if they were free roads.

Congestion tolls form the second type of tolls. These can be considered in two classes: congestion tolls on express facilities and congestion tolls applied, blanketfashion, to congested arterials. In each case, the proponents of these tolls have presumed that by reducing congestion on one road or in one area they are conferring benefits to society. These benefits are at best problematical, and may be negative. As Haikalis (16) has shown, travel on a congested expressway may be substantially less costly than travel on an uncongested arterial. Thus, forcing people by tolls off expressways may well increase total social costs.

Congestion tolls applied to arterials (which are generally congested throughout an entire area) would undoubtedly force some drivers off arterials onto still higher-cost local streets, or prevent them from coming to an area such as the central business district. It would be difficult to account for the complete social costs resulting from such a policy, but one could be sure of the unpopularity of such a measure.

Clearly, no hard and fast conclusions can be drawn in this paper on tolls and subsidies except to say that they affect only a small proportion of travel costs and are, hence, weak devices for controlling the flow of traffic.

The main point which the authors wish to make is that through the use of a model for constructing cost surfaces, such as has been suggested here, the alternative costs arising out of different investment policies can be studied quite easily. Such cost pictures, and the improved versions which will come in time, should be of substantial benefit to metropolitan management in the future.

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