The Comparison of Transport Technologies

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•OVER the past decade the transportation planning process has evolved into a rather sophisticated methodology for dealing with questions related to future investment in transport facilities—particularly highway facilities. Given any proposed change in the transportation network, it is possible to predict the consequences of this change that are associated directly with the transport system. However, at least two serious weaknesses in planning methodology remain. These are in the areas of developing alternative plans (1) and evaluating these alternatives in terms of their nontransport consequences (2).

At the present time there is very little basis upon which to develop transportation alternatives. There appear to be two reasons for this condition: (a) there exists only a weak understanding of the extent to which various types of transport services can assist in achieving various non-transport regional goals, and (b) there is little basis for making comparisons between transport technologies so as to enable rational choice of the technology mix that is to provide a set of services. The purpose of this research is to attempt to develop a framework that will permit a more comprehensive comparison of alternative technologies than has been possible in the past.

In the following section, a discussion and critique of earlier works in the comparison of transport technologies serves to identify the major strengths and shortcomings of methods employed in these studies and to sharpen our understanding of the requirements for a general comparison framework.

BACKGROUND

There have been a number of notable attempts to compare the characteristics of various existing and proposed transport modes. One might reasonably ask the question: Why do these not provide the framework necessary for the comprehensive comparison of various technologies? A review of these works would be helpful in answering this question and also in pointing out the direction of the research contained herein.

Perhaps the most ambitious attempt to compare the characteristics of various modes was the work of Meyer et al (3). This study was concerned with comparing the cost characteristics of the various existing (in 1955) modes. The basic measures used for comparative purposes were the long-run marginal cost per ton-mile for freight and per passenger-mile for the movement of persons. In the case of freight, cost was also considered a function of the size of the shipment and the length of the movement, and a distinction was made between three commodity classes (liquid, bulk, and manufactured) in the case of water carriers. For passenger traffic, a distinction was made between the costs for various types of accommodations on rail and air carriers.

One of the difficulties the authors faced was in dealing with differences among modes with respect to characteristics other than cost. This difference is most obvious in the time dimension, where the differences between, say, rail and truck freight, or air and bus passenger movement, are often orders of magnitude. Meyer et al tried to account for this in the case of freight by including in the cost of shipment a cost associated with the required in-transit inventory. No explicit treatment of this was found for person movement.

There were (and are), of course, many other differences between the services rendered by the modes considered by Meyer et al. Some of these are the location of access

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points and the effect on service and the need for feeder operations; variations in cost due to variations in location of origins and destinations relative to terminals; safety and comfort of persons; and damage to goods.

Using their comparison framework, the only means for dealing with these differences is qualitative. This is to directly associate certain characteristics of service with the institutional label of the mode. Perhaps this is adequate if one is solely interested in services of a type offered in the past. It is, of course, not adequate to deal with services and modes that depart from those of the past.

In a later work, which dealt with urban transportation, Meyer, Kain, and Wohl (4) developed a scheme for circumventing the difficulties of noncomparability found in the previous work. The scheme used involved the comparison of three modes (auto, bus, and rail) in an idealized environment. The services of each mode were made comparable—or as nearly comparable as technologically possible—and then the costs were compared. This enforced comparability took the form of requiring very short headways for common carriers so as to bring the waiting time close to that of the private automobile, and of requiring that a seat be given to each passenger, and so forth.

Having rendered the services as comparable as possible, it is assumed that users would be indifferent between the alternatives except insofar as their cost (or price) differed. Thus the criterion used to select one "best" mode from the alternatives is that of least total cost, for the desired level of output (capacity). In this manner the range of capacity for which each mode is "best" is identified.

The severe shortcomings of this type of comparison should be obvious. It fails to take into account the fact that different modes are inherently suited to provide different types of service. These differences relate not solely to capacity, but to many other service characteristics: frequency of departures, speed, the location of points of access, and price, to name a few.

A very commonplace situation can be used to illustrate this point. Consider two cities, which are connected by air and highway. Within a wide range of conditions, a plane trip would be faster and more expensive than an automobile trip (among many other differences). If you were to try to make these two modes comparable by reducing the speed of the aircraft and perhaps increasing auto speed to the upper limit of safety, you would be destroying an inherent characteristic of the air mode. It is doubtful that a cost comparison under these conditions would tell you very much about the types of services for which each mode is well suited.

There have been, of course, a number of studies of the economic and technological characteristics of individual modes. A notable example is the work of Land and Soberman (5). The authors present the technological or operating characteristics of urban transit and this leads into a discussion of cost functions. They do discuss many of the variables associated with the service rendered by this mode, but they do not develop any comprehensive cost or performance functions. Morlok extended their analysis to develop actual cost-output functions for a linear route (6). The measures of output considered were flow capacity, headway, station spacing, and speed.

These authors do not, however, discuss many variables that are associated with the spatial properties of the service. This is not a serious shortcoming in this instance, because rail lines are generally constructed in a radial pattern. However, if a rail network with highly interacting routes were under consideration, a means for dealing with properties of the network would be desirable.

Another example of this type of work is the book by Hay (7). Hay attempts to compare the technological, cost, and service characteristics of the major modes within a fairly comprehensive framework. This work is notable in that he does attempt to give a formal structure to the comparison, which brings to light many similarities and differences between modes which otherwise might be overlooked. The characteristics used as a basis of comparison are direct cost, transit or travel time, flexibility, reliability, damage, capacity, and price structure.

The major weakness of Hay's work is the absence of either qualitative or quantitative definitions of flexibility. This word denotes a set of characteristics that deal with the locational aspects of a service and with the extent to which a mode depends upon other modes for distribution services. These aspects of service are strongly related to most of the other more readily quantified characteristics.

A somewhat similar work on the subject of urban transportation technology has been written by Berry, Blomme, Shuldiner, and Jones under the sponsorship of the Transportation Center at Northwestern University (8). This book is notable in that the authors attempted to compare directly many distinct technologies, both conventional and novel, although their treatment of the automobile mode was somewhat brief. In marked contrast to some other works, these authors brought to light the inherent differences between modes with respect to the types and quality of service which could be offered. It is considerably more comprehensive in this sense than other studies of urban transportation technology.

From our standpoint, however, this book does not offer a usable framework for our comparison of intercity technologies. The reason is that the structure used in the comparisons is a rather loose one, and is not composed of rigorously defined elements, measures, and relationships. Here we are more concerned with making an advancement in methodology that will permit the making of strong, quantitatively based statements about different technologies.

We began our discussion with brief reference to transportation planning. It is appropriate to consider the methods used to characterize alternative technologies within the urban transportation studies. Even a cursory examination of these studies reveals that they consider only conventional technologies: automobiles, buses, and rail rapid transit (9). This is invariably justified by the assumption that no major technological advances in either private or public transportation will be made within the time horizon (usually 20 years) of the study.

This summary rejection of the possibility of significant technological breakthroughs is not wholly unrealistic, because of the extent of existing facilities and the (probable) high threshold cost of introducing a major technological change. However, the urban studies have done very little to advance our knowledge of the comparative characteristics of even those transport technologies that they consider. The major result of their studies in this area has been a set of cost-output quantity relationships defined on a linear route, that is, a route composed of a sequence of links (9, p. 4-5, 38-43, 81-98, 121-127). These have been helpful in deciding which of various roadway types (e.g., freeway, arterial street) would be most economical under various conditions. In some instances, similar curves have been developed for rail rapid transit.

There has been very little effort expended in attempting to deal with spatial and temporal aspects of the output of a system. Also, those cost functions that have been developed are invariably excessively simple, so that many variations of the spatial and temporal aspects of output could not be analyzed.

A concommitant characteristic of these studies is that often very few real alternatives are examined. Studies in large cities often examine three major alternative plans: one in which improvements are made only to the transit system, one in which only roads are improved, and one which involves some investment and operating changes in both public and private transport. The best of these three is obvious, because the first two can usually be rejected on intuitive grounds. Some variations within the third class of alternatives may be examined, in which case some "real" alternatives are considered and the conclusions of the study are not largely foregone. Partly because of this lack of concern for examining a wide range of alternatives, urban studies have done little to advance the characterization of transport technologies.

The foregoing comments have pointed out a need for the development of a framework for the comparison of various distinct transport technologies. This is becoming increasingly important, because the number and variety of new technologies as well as major changes in existing ones are increasing at a very rapid rate (10), and this situation is likely to continue with the entering of aerospace firms into the field. Perhaps the most concise statement of the need for research on the comparative evaluation of transport technologies is that by Lang (11) in the Foreword of a book on monorails:

> ...There has been little attempt made, for instance, to assess soberly the characteristics of our available transportation media and to compare them on their basic merits. It seems that partly as a result of this neglect we are not solving our problems as quickly as we should.

The need for this is also strongly implied in the work of Garrison and Marble (12, p.8) on the structure of transportation networks:

> One salient feature of the voluminous material on transportation is its heavy dependence on descriptive verbal expression and the lack of exact definition and generality in this expression.... Descriptive materials varying in completeness are available on most transportation systems, but the nature of these materials is such that they are not suitable for systematic study.... There are no good ways to compare information among systems or to put together pieces of information about an individual system and make statements about the system as a whole....

PURPOSE AND SCOPE

The purpose of this research study was to develop a framework of quantitative measures and relationships that will permit the direct comparison of the properties of diverse transport technologies. Our interest for comparative purposes focused on two areas: (a) the cost properties, and (b) the properties of the transport service provided. The former category includes such items as the investment in structures, land, and vehicles, as well as the cost incurred in operating and maintaining a system. The service provided by a system can be described only by a large number of variables, which relate to such properties as the location of access points, network configuration, flow capacity provided, frequency of departures, and many others. Part of this research is, therefore, concerned with the identification and quantification of measures of output capability and relating these to technological properties of the system.

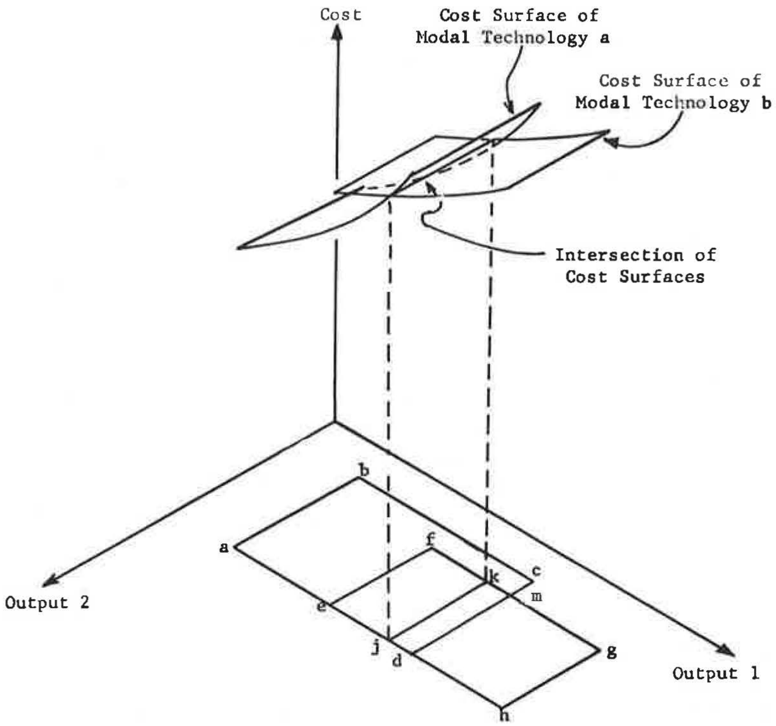
The results of this research can be viewed as consisting of two parts: (a) a vector of measures of the output capabilities of a transport system, which is related to the cost and technological properties of the elements of the system, and (b) a set of cost-output surfaces for three modes or technologies that were analyzed to test the efficacy of the approach. We are attempting to give a substantive structure to an area of study that has little basis at the present time.

In abstract terms, this research can be viewed in the following manner. We develop a vector of measures of the output capabilities of a transportation system, which describes a space which we call output space. By analyzing the physical performance properties of a transport technology, we find that portion of output space in which this technology can operate. An example of this is shown in Figure 1. Then we find the costs associated with each point in the output space and construct a cost surface on this space, after adding the appropriate cost dimensions. We can do this for any number of different technologies, and map the results onto the same space.

In order to find the types of service for which each technology is inherently suited, we need merely examine the cost-output surface for each technology. To illustrate the mechanism at work here, we refer again to Figure 1. For concreteness, we might consider the cost dimension to be total annual cost and the output dimensions to be average speed and flow capacity on a simple linear route, on which all other output variables are either of no interest or held constant. Technology a can operate over the output range abcd and technology b over the range of efgh. Although a can operate in the entire range abcd, it is not rational to use it in that range, for technology b costs less in the area djkm. Technology a should be used for outputs represented by abcmkj and technology b for outputs represented by jkgh.

Thus this scheme for analyzing transport capabilities for various technologies can result in information of the following types: (a) what the range of transportation outputs our technological capabilities enable us to produce is, and what levels of output we cannot now achieve, (b) how much it costs to produce any feasible level of output, and (c) which of the available technologies should be used at each point in output space.

Although we would like to develop this analytical methodology in such a manner that all modes of transportation could be included, this will be true only in a general sense.



Feasible Output Space of Technology a: abcd
Feasible Output Space of Technology b: efgh

Efficient Output Space of Technology a: abcmkj
Efficient Output Space of Technology b: jkgh

Figure 1. Simplified examples of cost-output space and representation of transport technologies.

The major elements of the framework and the relationships discussed will be sufficiently general and robust for this. However, the central focus of the research was on common carrier intercity passenger services. This serves to both cut down the magnitude of the task and to give it a specific orientation.

TRANSPORTATION SYSTEMS

Since this paper is conceptual in intent, a concern with definitions is a necessary prelude. Specifically, to be able to deal with the problem of comparing transport modes, we must suggest definitions for the terms transportation, transportation systems, and alternative transportation technologies.

Transportation

Our definition of transportation is drawn from the doctoral dissertation of Snell, in which he defines transportation as the translocation of objects, be they persons or goods, in physical space, in time, and in state (13, p. 52-57). State refers to such characteristics of an object as its monetary value and condition. Thus the product of the transportation of an object (in this case, a parcel of freight) can be represented in three-space as shown in Figure 2. The object is moved from location L_1 to location L_2, in a time interval $T_2 - T_1$; and the value of this good is increased from V_1 to V_2.

The transportation of many different objects, or of all objects—both goods and persons—could be represented within this framework. Of course, the number of dimensions used

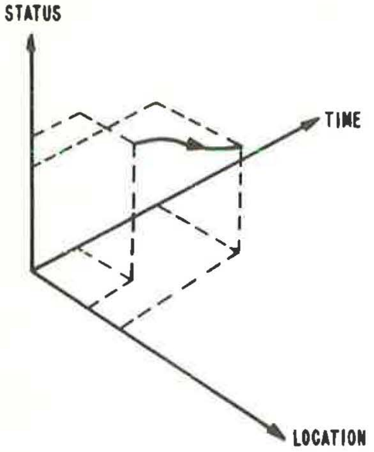


Figure 2. Transportation: The translocation of an object in location-time-status space.

to describe object state would have to be increased considerably, and many aspects of state for which we could not now give dimensions would have to be included in order to make the representation reasonably complete. In addition, a means of identifying each distinct object must be included, but this presents no conceptual problem. Thus we can define transportation as a change in the state of objects, in which each object is moved in time and physical space, and in which other attributes of each object are also likely to undergo a change.[1]

The closeness of this definition to that which is implicit in much of the regional science literature should be apparent. In the case of goods, the regional scientist usually describes the object (of transportation) by its location, the moment or period in time during which it is at that location, and its monetary value. Transportation will occur only when the increase in value resulting from the time-space translocation more than offsets the price paid for that transportation (15). Many of the conclusions of regional scientists regarding commodity flows and location decisions follow from this fundamental principle.

Transportation System

The definition of the transportation system rests in part upon our definition of transportation. We define the transportation system to be those physical objects and rules or procedures of operation which are engaged in the production of transportation. This definition is sufficiently general to include all of the current modes of transportation[2] and we feel will include any means of producing transportation likely to be available in the future.

As has been recognized in the transportation literature for almost 100 years, the various methods employed to produce transportation often display marked similarity. This is especially true among vehicular modes. The earliest published statement of and elucidation of this fact of which we are aware was written in 1870 (16); since that time there have been at least four others. Our conception of the elements of a transportation system differs somewhat from many of these, being based on what we feel are the basic functional elements of any system. These elements are (a) the way links, (b) the way interchanges (or intersections), (c) the terminals, (d) the vehicles, and (e) the control system. A definition (and example) of each of these, for the case of transportation of persons, is given in the following:

Boarding terminal—A facility which provides for the placing of travelers on the appropriate vehicle (or container), including processing of the traveler before boarding the vehicle. If the system is containerized, the transfer of containers between vehicle and the ground is included. (Airline terminal, including ticket sales, reservations, check-in and waiting areas, as well as restaurants, shops, etc.)

Alighting terminal—A facility which provides for the removal of travelers from a vehicle at their destination terminal or at vehicle transfer points. If the system is containerized, container transfer is included. (Same as above.)

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[1] This concept of transportation is very similar to the general world view of many computer simulation languages, especially Simscript. In this language the analog of our object, an entity, undergoes changes in its status as a result of its passage through time and the operations performed upon it (14).

[2] We have deliberately ignored the question of defining the word "mode" and will not use it in this paper in any context in which a precise definition is needed. The present usage often refers to technology, ownership, and legal status, and defies any rationalization.

Way link—A path on which a vehicle can move in space. (Roadway of an expressway, between interchanges.)

Way interchange—A facility which permits vehicles to move from one way link to another. It can have many entrances and exits. (An expressway interchange.)

Vehicle—The device which is the interface between the object and the way system and which gives mobility to the object. (A railroad train.)

Control system—The set of devices, decision-makers, and associated rules which provide for the efficient and rational operation of the remainder of the system. (A traffic signal.)

It should be fairly clear from these definitions that any vehicular mode of transportation designed to carry passengers will have elements which perform the functions described. Those portions of a system designed to carry freight will have a corresponding set.

Statements as to what constitute the functional elements of a transportation system have appeared occasionally in the literature. The earliest we found was in an article by Potts rather pretentiously entitled "The Science of Transportation" (16). In this work, the elements were way facilities and vehicles. Way facilities included links, intersections of routes, and terminals. Since the author was mainly concerned with rail transportation, vehicles included locomotives, freight cars, etc. It is interesting to note that no mention was made of a control system, apparently reflecting the technology of the era. Although the discussion was clearly influenced by the then-current transport technology, Potts attempted to describe the effect on transportation service of certain technological advances, ranging from more powerful locomotives to flying machines and fluid cushion vehicles flowing through an almost frictionless medium in a tube.

In 1894 Cooley wrote on "The Theory of Transportation" (17), in which he divided a modal system into a number of elements—the way facilities, vehicles, and motive force. His discussion was essentially historical, not analytical in the sense of Potts' work.

More recent statements as to the components of a transportation system include those by Hay (7, p. 113) and Snell (13, p. 96). In both of these works the elements are essentially the same as ours. In a more recent paper by Manheim (18), the list is similar to ours except for the description of all way facilities as nodes and links. This is based on one (very common) means of abstractly representing the way facilities, which is derived from the edge (link) and vertex (node) concepts of graph theory. However, we choose to use the classification of elements based on function rather than the representation in most models, because other means of representation are possible.

Transport Technology

Although we have used the word technology frequently, we have not defined it, instead relying on the reader's familiarity with the common meaning of the term. The field of economics does have a very specific meaning for this word. A technology is a specific means of producing a good, including the capital equipment, labor, raw materials, and rules of operation (19). Thus the economist's definition of a technology is a very complete specification of the means by which an item is produced. Indeed, if one can employ two different means to fasten two parts of an otherwise identical machine, each of these technically represents a distinct technology.

This definition of technology is not entirely suited to our needs, for it forces us to look at the world in far more detail than we need or care to. Therefore we are taking a more pragmatic approach to the definitional question and will use a less precise, but hopefully more useful, definition. To distinguish it from the economist's definition we will call it a "technology class." We define a technology class as a set of technologies which are capable of producing transportation and which are sufficiently similar that the hardware and labor characteristics and operating procedures can be described by essentially the same variables and relationships. Thus we would consider a railroad operating between two cities at one capacity-train frequency level and essentially the same railroad operating at another capacity-train frequency level as the same technology class. Since different quantities of manpower, cars, locomotives, fuel, etc., would be required for these two different outputs, these are distinct technologies in the economist's sense. However, a vertical take-off and landing aircraft system and a railroad would be considered as two different technology classes, even if their products in terms of places served, capacity, frequency, etc., were essentially the same. Rail and air are considered different technology classes because, for example, the equations and variables used to describe the aerodynamic lift properties of an airplane are not used—and presumably need not be used—in the design or analysis of railroad locomotives and cars.

It is important to note that this distinction between technology classes has been decreasing in recent years and is likely to become much less important in the future. The reason for this is that researchers in transportation engineering are realizing that methods of analysis of one technology class have much in common with methods used for another. For example, the algorithms used to find the shortest path from one place to another in a network are as applicable to the routing of aircraft or freight trains as they are to the modeling of motorists' route choice behavior. We feel certain that the number and scope of problems that are recognized as common to many technology classes will increase very rapidly, and with this the need for the distinction will wane. This will be due in no small measure to the recognition and treatment of problems at a much higher level than those treated in the past. The nature of these problems is such that more than one technology class must be considered and that they must be treated in much the same terms. An example of this sort of analysis is the urban transportation study, in which highway and rail rapid transit must be considered.

MEASURING THE OUTPUT OF A SYSTEM

In the preceding section we defined the output or product of a transportation system in terms of the movement of a single object—presumably a person or a single shipment of freight. While this gives us a workable definition, we clearly cannot perform analyses of major changes in the system and still treat each object as a separate entity, because the information handling requirements would far exceed our computing machine capabilities as well as our comprehension. Thus more aggregate measures of output must be developed, using as a basis the macroscopic definition of transportation.

Macro Viewpoint

The first change in output description made necessary by the macro viewpoint is that the dimension of quantity must be introduced. This permits the measurement of various aspects of the capacity of the system, and also permits the description of tradeoffs between the throughput of the system and qualities (such as time) of the product.

The second, and more difficult, change relates primarily to the time, location, and state dimensions. We are essentially concerned with measuring the general output capabilities of a system, not with the actual output in terms of the change in the state of particular sets of objects. Moreover, we would like to measure the output capabilities in terms of characteristics as independent of the particular set of objects that use the system as possible.

It is not possible at this time to demonstrate that this is in fact possible. However, we can suggest ways of handling the time, location, and state dimensions in such a manner that this independence is at least a very reasonable possibility. We shall treat each of the three dimensions separately.

In the case of location, the problem of aggregation has been partially solved in transportation planning studies by dealing with a finite number of zones, each with non-zero area, rather than continuous space, or a continuum of points. The tremendous mathematical complexities introduced by a continuous representation of space—even for relatively simplified problems—appears to be well recognized and accepted. To our knowledge, only two published research studies—one by Beckmann (20), the other from the staff of the Chicago Area Transportation Study (21)—have reasonably successfully dealt with problems in a continuous spatial context. However, when using the zonal representation, the size and boundaries of the analysis zones must be made so that the approximation is reasonable in relation to the purpose of the analysis.

TABLE 1

MEASURES OF PASSENGER TRANSPORTATION SYSTEM OUTPUT CAPABILITY

- Individual path between one origin and one destination:
  - Time vector
    - Total trip time
    - Waiting time (or departure frequency)
    - Vehicle(s) running time(s)
  - Cost vector
    - Fare or other out-of-pocket charges
    - Cost of other items (meals, lodging, etc.)
  - Comfort and convenience vector
    - Number of vehicle transfers
    - Availability of passenger services (meals, entertainment, etc.)
    - Ease of ticketing, reservations
    - Physical environment (temperature, pressure, cleanliness, etc.)
    - Psychological value (status, privacy, etc.)
    - Other values of trip (scenery, acquaintances, etc.)
    - Safety (probability of injury, death)
  - Quantity vector
    - Flow capacity
    - Storage capacity
- All reasonable paths between one origin and destination:
  - Ranges of values of elements of time, cost, quantity, and comfort and convenience vectors
  - Trade-offs between values of elements of time, cost, quantity, and comfort and convenience vectors
- Entire region under analysis:
  - Location vector
    - Density of access points
    - Density of routes
    - Network connectivity, redundancy
  - Time-space vector
    - Speed (or unit travel time)
    - Fraction of time spent waiting, moving, etc.
  - Cost-space vector
    - Cost per unit distance
    - Threshold cost
  - Comfort-space vector
    - Transfers
    - Fraction of access points with various types of passenger services
    - Amenities, scenery
  - Quantity-space vector
    - Flow capacity per unit area
    - Storage capacity per unit area
  - Ranges of values of elements of these vectors
  - Trade-offs between values of these vectors

Once the problem of measurement of location is solved, one can deal with the other dimensions. Since the zonal representation is most common, we shall limit our discussion to this type of spatial representation, although much is transferable to the other representation. The other dimensions of output are treated on a zone-to-zone basis, perhaps with distinction between classes of objects within each zone. In the case of time properties of the system, there are no major difficulties. Measures such as origin-to-destination travel time and the components thereof, frequency of departures (if service is scheduled), and time spent in various qualities of environment are readily constructed. Since we can measure time objectively, the measure is independent of the particular user.

It is much more difficult to achieve this independence with respect to other state change measures. Part of the reason lies with the fact that we do not have sufficient knowledge to state what these measures should reflect, particularly in the case of person movement. There is no operationally defined and measurable person analog to the market value of a good, for example.

We are thus forced to suggest measures which, based on our intuition, are probably significant causes of state changes on the part of users. Such items as the number of vehicle transfers, the availability of meal service and rest rooms, and the temperature and wind level of the area in which one must wait for a common carrier vehicle are measures which come to mind. Items such as those suggested can be measured objectively.

A list of specific measures that might be used to describe the output capabilities of a person transport system is given in Table 1. Each of these could be used to describe the capability between each pair of zones, or further aggregation could be made. Each measure potentially refers to a distribution of values, not necessarily a single number.

Our feeling that characteristics of a transportation system can be measured objectively is supported by some of the recent thinking of economists in the area of consumer demand behavior. Goods are no longer described solely by their name, e.g., an automobile, but by a collection of characteristics which the consumer purchases, e.g., speed, seating capacity, luggage capacity, and operating costs. As is described in a recent paper by Lancaster (22), this treatment of demand results in a much richer and more useful theory than the classical approach.

One central assumption of the reformation of demand theory is essentially ths same as our assumption that the output of a (transportation) system can be described objectively (22, p. 134):

> We shall assume that the structure which we have interposed between the goods themselves and the consumer's preference is, in principle, at least, of an objective kind. That is, the characteristics possessed by a good or a combination of goods are the same for all consumers and, given units of measurement, are in the same quantities, so that the personal element in consumer choice arises in the choice between collections of characteristics only, not in the allocation of characteristics to the goods.

Examples

Very similar in outlook is the recent work of Baumol and Quant in developing a model to predict person movement between areas of the Northeast Corridor via each of many possible present and future "modes" or alternative means of travel (23). Their work is an example of the application of Lancaster's approach to explaining consumer behavior. Baumol and Quant describe the product that a traveler purchases in making a trip by (a) the origin and destination, (b) total travel time, (c) the cost or price, (d) the frequency of departures, and (e) the relationship between alternatives with respect to these variables (23, p. 12-13). Although the empirical testing of their model is incomplete, the results appear encouraging (23, p. 19-25).

The measures used by Baumol and Quant are examples of one class of measures which can be derived from the definition of transportation. Again referring to Figure 2, the measures they use would be:

1. Origin and destination, L_1 and L_2;
2. Total travel time, $T_2 - T_1$;
3. The cost or price, which is measured on the status dimension as the change in the money the traveler has as a result of making the trip, $V_2 - V_1$ (in this particular case $V_2 < V_1$, contrary to the relationship in the figure);
4. The frequency of departures, which would be shown as the alternative times at which the traveler could move in certain portions of the space from L_1 to L_2; and
5. The relationship between alternative means of travel, which would be determined by comparing measures 1 through 4 for all alternatives.

All but the first of these measures involve a subtraction of measures associated with the object (passenger) at the origin and destination of the trip. These are simple status change measures, as is the first.

Other classes of measures are suggested by the model and are actually in use. The first of these is the rate measure, most commonly found as a measure of speed, e.g., $(L_2 - L_1)/(T_2 - T_1)$. Also, one could measure the rate of change of value of status (other than location) with respect to time. For example, the rate of deterioration of perishables could be measured as $(V_2 - V_1)/(T_2 - T_1)$. For person movement, time-cost trade-offs could be measured in this manner.

Furthermore, composite measures, such as passenger-miles, or passenger-miles per hour, can be derived from the model after the addition of the quantity dimension. If the superscript i were used to designate each object in the system, then the summation over all objects in a particular (spatial) area or in a particular time interval could be made. If $L^i(T_j)$ means the location of object i at time T_j, $f\left[L^i(T_j) - L^i(T_k)\right]$ denotes the distance moved in the interval T_j and T_k, and if Q^i is the quantity of i, then the passenger-miles per unit time of a system would be measured as

$$\frac{\sum_i Q^i \cdot f\left[L^i(T_2) - L^i(T_1)\right]}{T_2 - T_1}$$

The rate of unidirectional flow past a point is measured by $\sum_{i} Q^{i}/(T_2 - T_1)$, where i is summed over the appropriate objects. Thus there exists a very large number of possible output measures, ranging from simple status change measures to rates and complex measures.

Regardless of the exact form the dimensions and measures of the output of a transportation system take, the result is the specification of a vector by which the output of a system can be described. This vector defines a space, which we shall call transport system output space. The vector elements may correspond to those listed in Table 1, or they might differ according to the problem under analysis.

SAMPLE ANALYSIS

An example of the type of analysis proposed in previous sections is presented in order to illustrate its feasibility and potential use. While this example relates to high-speed intercity transportation, the applicability of the same methods to urban transportation will be pointed out and inferences about urban transportation analysis will be drawn in the concluding section.

The Problem

The specific problem considered is that of the comparison of three technology classes that are available for intercity transportation of persons—high-speed railroad system, vertical take-off and landing aircraft (VTOL) system, and a bus system in which the vehicles operate on conventional roads and freeways (24, p. 122-158). These were chosen in part because they represent some extremes in technology and in part because data on the cost and physical performance properties of each were available. Of course there are many other interesting and viable technologies, such as tracked air-cushion vehicle systems.

Definition of Output Space

The dimensions used to define the output space for the example problem reflect the purpose of the analysis: to provide a broad statement of the relative capabilities of each of the technology classes. The generality of this purpose dictated a very concise statement of output but also required that a very broad range of alternatives be capable of inclusion. The coarseness of the output space used here reflects these desired properties.

The most convenient means of exposition of the dimensions of this space is by considering a sequence of questions about the system. First, there is the question of where a person can travel, in the sense of what places are served. Then we could ask how, meaning via what routes or links, interchanges, and terminals. Third, the question of the amount and qualities of the transportation service offered between various places arises.

The first question is answered by the variable terminal density, measured by such units as terminals per square mile. As the value of this variable increases, more places are directly served and the ease of access to the system is increased. If reference is made to a particular region, the value basically determines which places are served.

The question of how these places are connected with one another is much more complicated, and really requires a group of measures in order to be answered. These measures are related to the concept of the connectivity of a graph, a graph being one means of abstractly representing a transport network. A graph is basically a set of vertices (points) and edges (lines), as shown in Figure 3. Connectivity is defined as the ratio of the number of edges of a graph divided by the maximum number which could exist (12, p. 22-24). If we limit ourselves to graphs in which only one edge can connect the same pair of vertices (simple graphs), and to those in which no edges can intersect except at vertices (planar graphs), this measure is

$$C = \frac{e}{3\,(v - 2)}$$

where C = connectivity, e = number of edges, and v = number of vertices.

The measure, connectivity, is very useful in distinguishing between various network configurations, as is shown in Figure 3. Its power in this connection is also demonstrated by the fact that the three classical transportation network patterns are distinguished as follows (24, p. 89-101):

Spinal, $\frac{1}{3} \leq C \leq \frac{1}{2}$, $v \geq 4$
Grid, $\frac{1}{2} \leq C \leq \frac{2}{3}$, $v \geq 4$
Delta, $\frac{2}{3} \leq C \leq 1$, $v \geq 3$

Thus this measure appears very useful as an indicator of network structure.

At first glance it would seem that terminals should correspond to vertices and the links between them to edges. This was not found to be the most useful representation, however, because most real world networks would then have connectivities less than two-thirds and much of the distinguishing power would be lost. Rather, interchanges—places where links intersect—were taken as vertices, and links between interchanges as edges. Terminals then could occur on a link.

This enabled one to change the scale of a network by simply changing the distance between interchanges, without necessarily changing the connectivity, the descriptor of the shape of the network. For example, with identical terminal locations, we could have a grid in which each terminal was the intersection of four (or two or three, in the case of terminals on the outer edges of the graph) links. Alternatively, the grid pattern

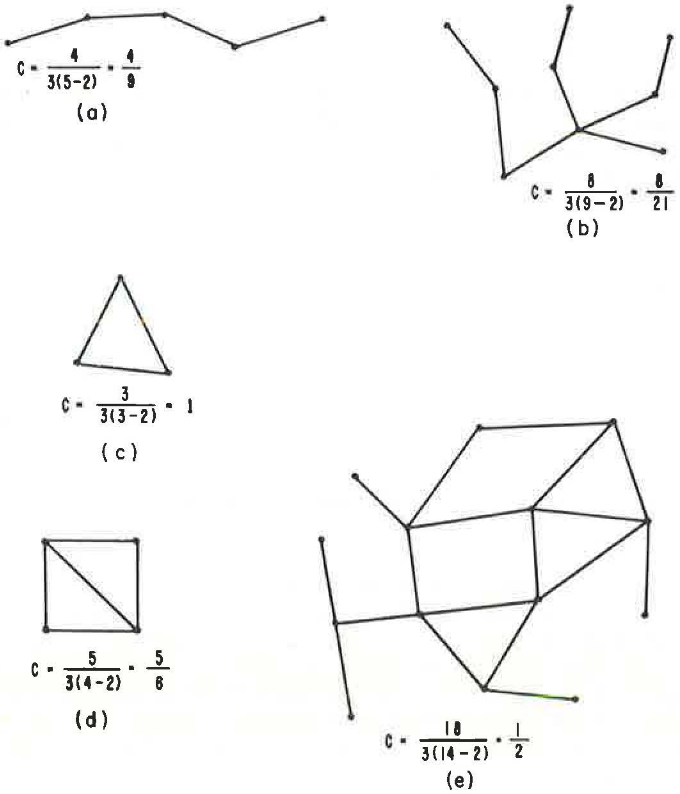


Figure 3. Examples of planar graphs and associated values of connectivities.

might be retained but only every other terminal might be such an intersection, with the intermediate terminals being on a continuous link. The connectivity measure defined on interchanges would be about the same for both, indicating the similarity of shape. Only the scale, as measured by interchange density, number of terminals per link, and link length, would differ. The portion of the system represented—consisting of the terminals, links, and interchanges—is conveniently described as the fixed network. This is in contrast to the flow or service network, which refers to the movements of vehicles on the fixed network.

The basic concept of the vehicle flow network is that of the vehicle service group. This is defined as a set of vehicles that follow the same path and make the same stops as one another, the only difference being in the time. An example of this is the set of trains that operates between New York and Washington, which follow the same route, shuttle back and forth, and make (almost) identical stops. Other examples are the express buses and air shuttle between the same cities.

Considering just a single service group, we can readily deal with two key dimensions: time and quantity. First, as for travel time between terminals, the time-distance curve is readily computed, given the route and vehicle characteristics. Another aspect of time is when movement can occur. Here we simplified reality by assuming a regular schedule, such as one departure per hour, except during two 2-hour peak periods, when departure rates are in integer multiples of the base rates.

Second, as for quantity, the common flow capacity measure of seats per hour was used.

Other important aspects of system output refer essentially to status change or perceived costs for which we now only have crude measures. One important class of these relates to the necessity of vehicle transfers on a trip. This was measured by the average of the number of other terminals to which one could travel from a single terminal without a transfer. Another aspect is the extent of express service, measured by the average of the number of other terminals to which one could travel from a single terminal without an intermediate stop.

The other measures used are availability of rest rooms, meal and beverage service, and volume of space per seat. As each of the modes was operated, these aspects of service were necessarily different, but alone probably would not have a great effect on patronage.

It is recognized that many other aspects of service are important from the user's viewpoint. However, the measures actually used in the analysis were limited to those given, in order to keep this first use of the comparison framework tractable.

Cost Functions

Cost functions were developed for each of the technologies—bus, rail, and VTOL—in which the output variables given were the independent variables. In some cases, bounds were placed on these due to limitations of the particular technology in question. Total annual cost—including annual capital cost and operating cost—was the dependent variable. Capital costs included the costs of vehicles, terminals, way facilities including right-of-way, maintenance equipment, and control facilities. Operating costs included those for labor, fuel, maintenance, terminal operation, and management. In the case of joint use of facilities (e.g., terminal) or internal services (e.g., management), with another "mode" (e.g., freight rail service), only the marginal costs are assigned to the modes under consideration. These relationships drew heavily from work done for the Northeast Corridor Transportation Project (24, p. 147-158) and the functional elements of the transportation system given earlier.

Two types of analysis were performed using the cost functions and output space. These were analysis of trade-offs possible within each mode and a comparison of total costs. The purpose of these analyses is to give some indication of the range of choices as to output variables that exist for each mode and to compare them over the relevant range. In this manner an indication of the types of services for which each is suited is given. There are basically two comparisons, one corresponding to variables associated with the service network and the other corresponding to variables of the fixed network.

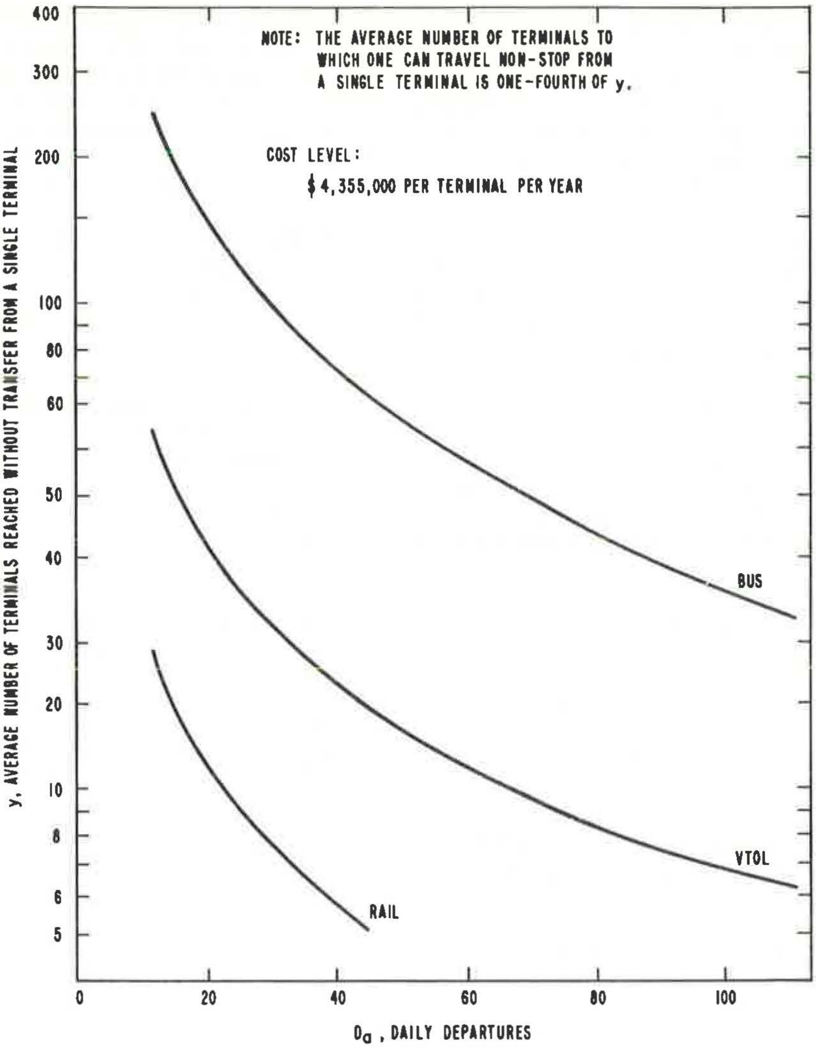


Figure 4. Trade-off between departure frequency and the number of terminals reached without vehicle transfer for rail, VTOL, and bus, at equal cost levels.

Trade-Off Analysis

The first comparison involves the relationship between the modes in terms of the two variables, (a) daily departures of each service (D_a) and (b) the average number of terminals to which one can go without transfer from a single terminal (y). The analysis considers only the cost of the service network, since there is no required change in the fixed network as these service variables change.

The results for the three modes are shown in Figure 4. The annual cost of each mode, per terminal, was held at $4,355,000. This number was chosen so that the rail curve would pass through the point ($y = 10, D_a = 23$).

The order of the modes in terms of the service variables y and D_a is unambiguous, with bus wholly dominating air and air wholly dominating rail. This ordering is precisely the inverse of that for speed, as shown in Figure 5. Thus, in terms of these three levels of service variables, no one mode dominates any other. Hence, there may be a market for each along the same route.

The reader may wonder why we do not compare the modal level of service trade-offs when the costs per unit of capacity are made equal. While this would be interesting, it is not, in general, possible. The costs of rail can only be reduced to those of bus when trains are exceedingly long—about 30 cars. Also, bus costs and air costs per unit of capacity cannot be made equal, as a moment's reflection will reveal. The ordering of service network costs per seat-mile from lowest to highest, is bus, rail, and air.

If one is only interested in departure frequency and the number of destinations reachable without transfer, and not in capacity per se, one can compare the costs of rail, air, and bus. A level of service trade-off curve coinciding with that of rail in Figure 4, costs $388,300 per terminal with the bus technology and $1,513,900 per terminal with VTOL technology. Thus bus costs are but 9 percent of rail and VTOL costs are only 35 percent of rail. However, there are such substantial differences in capacity that cost per seat-mile of bus is fully 71 percent of that for rail and the cost per seat-mile of air is 146 percent greater than that of rail. It should be borne in mind that there are other level-of-service differences, too, such as those with respect to speed and with respect to the very subjective area of comfort.

A second type of comparison refers to essentially spatial properties of their output, assuming reasonable levels of output with respect to vehicle flow properties. We are specifically concerned with the density of terminals (or the inverse, the tributary area) and the fixed network connectivity.

Here the terminal density, N′, is taken as a measure of the difficulty of gaining access to the intercity system. This difficulty increases with the area served by a terminal, and hence is inversely related to terminal density. Connectivity, C, is a measure of the ease of travel between terminals—assuming there is a vehicle flow on each way link, as is only reasonable. The greater the connectivity of the system, the more direct is travel between the points served. The tendency is toward reduced travel time, more places to which one can travel non-stop or without transfer, and greater capacity, ceteris paribus.

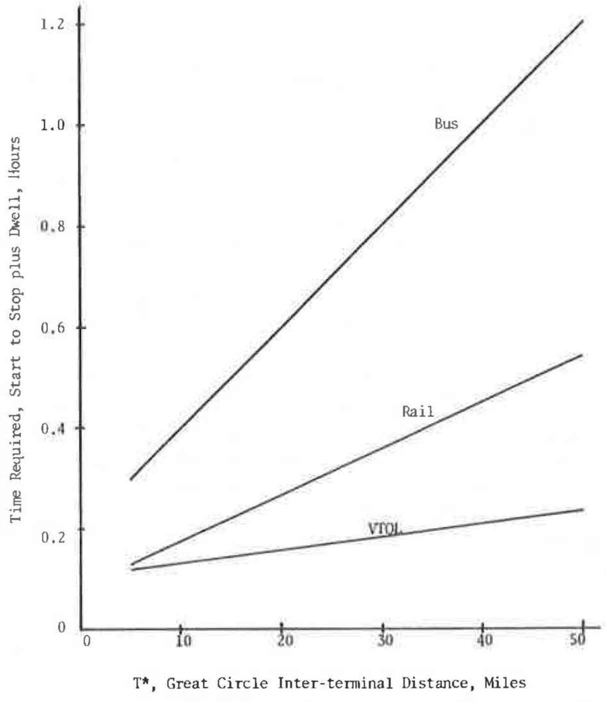
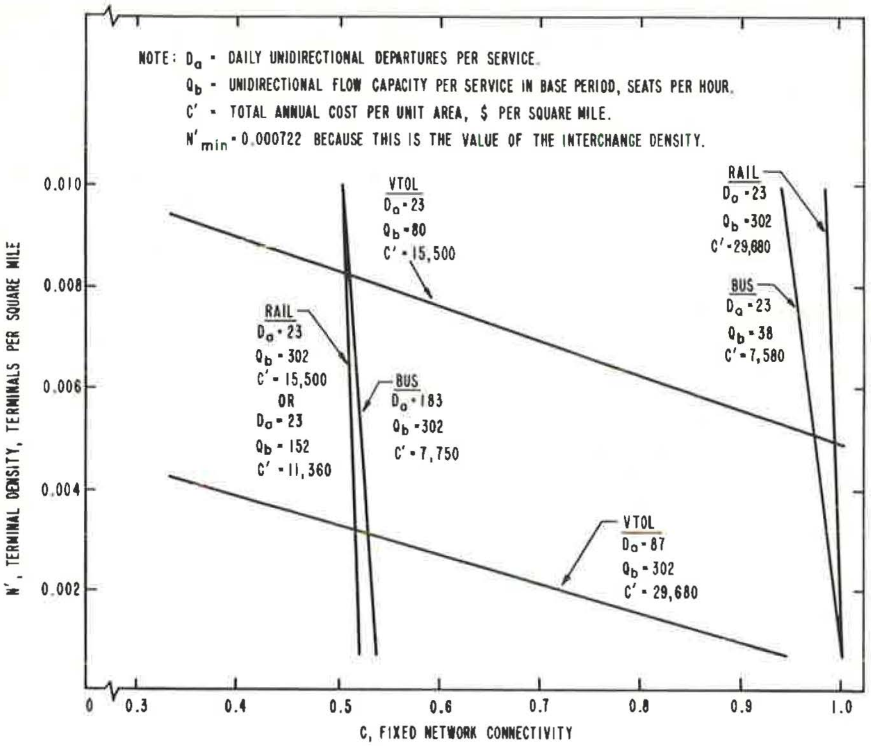


Figure 5. Modal time-distance curves including effect of circuity.



NOTE: D_a - DAILY UNIDIRECTIONAL DEPARTURES PER SERVICE.
Q_b - UNIDIRECTIONAL FLOW CAPACITY PER SERVICE IN BASE PERIOD, SEATS PER HOUR.
C' - TOTAL ANNUAL COST PER UNIT AREA, \$ PER SQUARE MILE.
N'_{min} = 0.000722 BECAUSE THIS IS THE VALUE OF THE INTERCHANGE DENSITY.

Figure 6. Trade-off between connectivity and terminal density for each mode.

The level of service assumed for this analysis is for each link to be used by two service groups. This corresponds to twice the minimum level of service required to just cover the network. On the average, a service group serves five terminals. The number of departures for all modes and the size of trains was varied so that comparisons at different levels of output could be performed. Link length was set at 40 miles and interchange density at 0.000722 per square mile, i.e., each interchange "serves" 1,385 square miles. This was based on interchanges having a hexagonal "tributary" area, which permits the widest range of network types.

The trade-off curves for the three modes under consideration are shown in Figure 6. The lower bound on terminal density is identical to the interchange density. The upper bound for analysis is somewhat arbitrary, but reasonable in that it corresponds to an inter-terminal spacing of about 5 miles. The limits on connectivity are self-explanatory.

The base level of flow capacity for this comparison was taken as that produced by rail with four-car trains, at a base period headway of one hour, for each service. This corresponds to a flow capacity of 604 seats per hour per link in each direction during the base period. Peak headways are one-half of base; hence, peak period capacity is 1,208 seats per hour per link. Since we have assumed a 60 percent load factor, these correspond to 364 passengers per hour (in each direction) during the base period and 725 passengers per hour (in each direction) in the peak periods. Because the carrying capacity of both buses and VTOL aircraft is fixed, it is necessary to operate 183 bus departures per day or 87 aircraft departures per day, per service, to produce a flow capacity equal to that of the trains. Other levels of vehicle flow (and hence capacity) were examined for all modes, also.

The trade-off between connectivity and terminal density is shown for selected values of daily departures in Figure 6. Even at the relatively high capacity of 604 passengers per hour (base), the bus is cheaper than either rail or VTOL, at any particular level of connectivity and terminal density. This holds true for capacities many orders of magnitude larger than that quoted— values well beyond anything reasonable. At the stated flow capacity, and a connectivity within 5 percent of one-half, bus costs per unit area are only about one-quarter to three-tenths those of rail. As connectivity increases, the relationship is slightly more favorable to the bus. Bus costs are always less than one-half those of air, although the fraction varies considerably over the range of C and N′. However, as has been pointed out before, other values of the bus output vector are necessarily not equivalent to the rail or VTOL system. These include speed, availability of meal and bar service, and size of seat, etc.

TABLE 2

OPERATING SCHEMES FOR RAIL-VTOL AIRCRAFT COST COMPARISON

Scheme	Flow Capacity[a]		Assumed Usage[b] Per Way Link, Passengers Per Hour
	Per Service, Seats Per Hour	Per Way Link, Seats Per Hour	
1	151	302	181
2	226	452	271
3	302	604	362

Scheme	Daily Departures Per Service[c]		Train Length, Cars
	VTOL	Rail	
1	44	23	2
2	66	23	3
3	87	23	4

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[a] Capacity figures refer to base period flow rates, unidirectional.

[b] Based on 60 percent load factor.

[c] Departures along each way link are twice these numbers.

The figure clearly illustrates the fact that bus and rail costs are essentially determined by the level of connectivity and are relatively independent of terminal density. This is indicated by the slope of the iso-cost lines, which show that a large reduction in terminal density will purchase only a very small increase in connectivity. This is not the case with VTOL. Here a reduction in terminal density from, say, 0.0004 to 0.0002 terminals per square mile, along an iso-cost curve, $29,680 per square mile, will purchase an increase in connectivity from 0.37 to 0.72.

This figure also indicates that VTOL is not always inherently better suited to highly connected networks than high-speed rail. Consider the example of desiring a flow capacity of about 300 seats per hour per link (or 180 passengers per hour per link) for which you were willing to spend about $11,350 per square mile. With rail technology this will buy a connectivity of about 0.5, regardless of terminal density. Using VTOL technology, there is a range of choice of connectivity of from 0.33 to 0.68 and of terminal density from 0.00072 to 0.0026 terminals per square mile. The rail and VTOL curves intersect at C = 0.52 and N′ = 0.0016. At values of connectivity less than 0.52 and terminal densities greater than 0.0016, rail has a lower cost than VTOL.

Total Cost Comparison

In order to find the combinations of connectivity and terminal density for which VTOL aircraft technology is less expensive than rail, and vice versa, the locus of points at which their respective cost surfaces coincide was found. This locus is dependent upon the level of flow capacity, or, more precisely, the number of departures of airplanes and trains, and the length of the trains. Loci were found for the combinations of capacity and daily departures shown in Table 2. These loci are shown in Figure 7. The locus for a capacity of 604 passengers per hour per link lies entirely below the minimum terminal density line. Rail is less expensive above this line, so VTOL is never cost optimal at this high level of capacity. This level of flow corresponds roughly to that on the main New Haven-New York-Washington rail route (25), but traffic between Philadelphia and New York is considerably heavier. This level of traffic on one mode may be rare or nonexistent elsewhere in the corridor.

The two other curves point out the strong influence of both connectivity and terminal density on the choice of cost-optimal mode. As connectivity increases, the range of terminal densities for which VTOL technology is least expensive increases. Also, as the desired level of flow capacity decreases, the larger the portion of the terminal density-connectivity space for which air is least expensive.

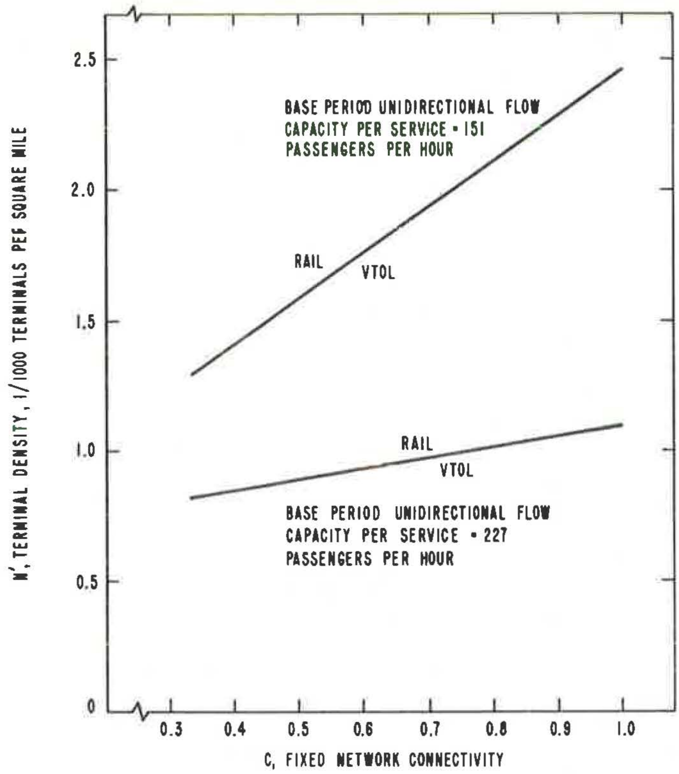

Figure 7. Rail-VTOL equi-cost frontiers. (Each line refers to a specific level of flow capacity. If the output desired lies above the line, rail is less expensive than VTOL. If the desired output lies below the line, VTOL is cheaper.)

Sensitivity of Results

Because of the speculative nature of many of the estimates of cost and technological performance parameters, particularly with respect to VTOL aircraft, it is important to discuss briefly the effect of changes in these parameters. As for the bus mode, it is clear from the cost values of Figure 6 and earlier figures that it is likely to retain its cost advantage regardless of any likely changes in parameter values. Similarly, it is likely to remain the slowest of the modes.

The loci of equal VTOL and rail costs, however, are very susceptible to change due to variations in parameters. If the cost associated with VTOL terminals were to be decreased, the slope of the iso-cost lines of Figure 6 would decrease; in other words, the N' intercept would increase and the C intercept would remain fixed for the same total cost. Similarly, if the cost parameter associated with connectivity were to drop, more connectivity could be purchased for the same total cost. These same effects hold for both rail and bus, although with these technologies the uncertainty of the estimates is less.

The same changes will affect the equi-cost loci of Figure 7. As the cost associated with terminal density is reduced, the N' intercept of the loci is increased, at both $C = 0$ and $C = 1$, and the entire curve is shifted upward. As the cost parameter of connectivity is decreased, the N' intercept at $C = 1$ is increased, but that at $C = 0$ is unchanged.

A large-scale sensitivity analysis of the results was not undertaken as part of this study. This was not considered appropriate for two reasons. First, the purpose of this research was to develop a methodology or framework for the quantitative comparison of the cost-output properties of transport technologies, not to obtain better estimates of the parameters that describe each element of a transport technology. Second, there appears to be no basis in the literature for making estimates of the likely range of values of parameters, since only point estimates were given for most of these. It seems extremely premature to conduct sensitivity analyses at this stage in the development of the comparison methodology. It is appropriate that we return to this methodology, and in particular to the discussion of Figures 6 and 7.

It is likely that link flows will be below 400 passengers per hour (unidirectional) on high-speed common carrier links in most of the corridor. Also, we strongly suspect that terminal tributary areas of 300 to 1000 square miles are likely to be of greatest interest. If these suppositions are true, then the choice between VTOL and a high-speed rail system (resulting from fixed facility and vehicle improvements to existing rail lines) is not obvious. Both may be substantially in evidence, each serving its own territory. Hopefully, rational planning would provide for close coordination, so that these two technologies could operate in what the traveler would view as one high-speed system.

CONCLUSIONS

This research has been an attempt to develop a framework within which the type of transport service for which a transport technology is inherently well-suited can be readily identified. In our review of previous work in this area we found that a major weakness has been the lack of a complete characterization of system output, so that the capabilities of diverse technologies could not be compared. Therefore, much of our effort was directed toward identifying the dimensions and developing operational measures of system output. The measures developed drew heavily from the abstract notions of graph theory, as well as the more concrete concepts of location, time, and quantity. These dimensions form transport system output space.

Each transport technology can operate within a certain portion of this output space, which we call the feasible output space for that technology. Since the feasible output spaces of two or more technologies often overlap, we are interested in their relative resource use in producing similar levels of output. Also, we are interested in knowing what it costs to produce the level of output associated with each feasible point in the output space. To enable us to estimate cost functions of various technologies, we developed a generalized transport cost model, in which we associated fixed and marginal costs with each of the functional elements of a vehicular transport system. In this manner, we have developed a general cost-output space within which various transport technologies can be compared, and within which the region of output space for which each technology is inherently suited can be identified.

To test the efficiency of this theoretical development, we compared three technologies with it: vertical take-off and landing aircraft, high-speed rail, and bus. The ease with which modal cost and performance parameters were transformed into those of the functional model indicated the soundness of the representation. We then used this representation to construct actual cost-output functions for these technologies, using the dimensions of our output space. The costs and values of the components of the output vector corresponding to each of the technologies were compared, and many statements regarding the type of transportation service for which each is suited were made.

Briefly, the conclusions were that, for the Northeast Corridor situations examined, bus system costs tend to be lower than rail or air system costs for reasonable levels of output. However, the difference between the values of many variables of the output space makes the bus mode inferior with respect to some level of service properties. The feasible output space for rail and VTOL aircraft systems intersect, except for the speed dimension (where VTOL is superior), so that these technologies are very close substitutes in some regions of output space. In this output region that is feasible for both technologies (ignoring speed), the cost surfaces also intersect. Rail is preferred at low values of connectivity, high values of terminal density, and high levels of link flow capacity. In terms of output variables associated with only the service network, such as frequency of departures and the opportunities for non-stop and non-transfer travel, there exist very substantial trade-offs with cost constant in all three of the modes.

From these comments, it is clear that a good or an efficient transportation system for a region as diverse in activity patterns and density as the Northeast Corridor is likely to be one that includes many different technologies. Each of these would perform where it is relatively best suited. Hopefully, intermodal coordination will be such that the traveler can easily make use of the entire system and not be artificially restricted in intermodal transfers.

A number of inferences can be made about the analysis of urban transportation systems from this study of intercity systems. The first is that the comparison methodology presented here probably could be applied to urban technologies and situations. Of course, the specific measures of output used probably would require change. This type of analysis would assist, however, in the determination of what types of service each existing or new technology is suited for. This in turn should aid the transportation planner in developing better plans.

This study points out the existence of two distinct types of transportation alternatives, whether they be for an urban area or a megalopolitan region. On the one hand we have technological alternatives—represented by the automobile, rail rapid transit, bus rapid transit, the Starrcar, etc., and we have transportation system alternatives—represented by different points in a system output space. Most of the debate on urban transportation alternatives seems to be about technological alternatives. Yet there exists a very large number of significantly different alternatives which employ the same mode (or modes) but are distinguishable in terms of travel time, capacity, and other system output properties, as well as price and usage controls. This latter class of alternatives is just as important as the former—perhaps more so. It deserves as much attention, for it reflects the issues of the general qualities and quantities of transportation capability to be provided in a region, not just essentially how the transport capability will be produced.

The use of a comparison framework such as that presented here would aid in the identification of the range of alternatives that exist for an area. It would help to identify the bounds on systems and to indicate the direct costs associated with the various alternatives included within the extremes. Hopefully, this would uncover alternatives not now considered, and this would potentially improve the programs of transportation investments suggested by the studies. If the resulting plans drew from alternatives that would not have been considered in the absence of the formal comparison methodology, the program is presumably a better one as a result. Even if the plan does not draw from newly uncovered alternatives, however, the certainty with which the planners feel the recommended plan is best in terms of their criteria is increased, for more alternatives were considered and rejected. In either case, the planning process benefits.

The relationship between what we have attempted to do and the planning process is succinctly stated by Heymann in "Transport Technology and the 'Real World ' " (26):

> ... What the planner can do here is not to select a single best transport system, but to marshall the data on the costs of alternative transport systems that will achieve different combinations of objectives.
>
> ...the transportation planner should attempt to present to the community a series of feasible, efficient alternatives....

We hope that we have made a contribution to this effort and to the emerging science of transport systems analysis.

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