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Seventeenth Annual Meeting

Theme:
"Beyond The Bicentennial:
The Transportation Challenge"

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TRANSPORTATION RESEARCH FORUM

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THEORIES OF PASSENGER travel date back over 100 years. However it has only been recently that large-scale comprehensive transportation plans have made use of any meaningful analytical techniques. Roughly 20 years ago the first such analytical technique was developed; it was called the Urban Transportation Model System (UTMS) or Urban Transportation Planning (UTP) process. It established the framework for estimating travel demand in four sequential steps: trip generation, trip distribution, model split, and traffic assignment. As a general process, UTMS is the most widely used transportation systems analysis approach today. Nevertheless, it has come under heavy criticism recently. As a result, alternative techniques have been receiving a great deal of attention.

One of the most attractive techniques which has emerged recently is an offshoot of the direct demand modeling which was undertaken as a part of the Northeast Corridor Project for the Federal Highway Administration; that is, equilibrium analysis. Relying heavily on basic economic theory, equilibrium analysis as applied to transportation states that: the flows that will result from a particular transportation system (T) and a particular socioeconomic activity system (A) can be determined by finding the resulting equilibrium in the transportation market. If $V =$ volume of flow, $L =$ level of service associated with the volume V, and $F = (V,L) =$ flow pattern, then it is possible to find the system equilibrium by establishing a supply function (S) and a demand function (D) and by solving for equilibrium flows (F) consistent with both relationships (1):

$$\begin{bmatrix} L = S(V,T) \\ V = D(L,A) \end{bmatrix} \longrightarrow \begin{bmatrix} F_o = (V_o, L_o) \end{bmatrix} .$$

Most of the original work in this area was concerned with estimating passenger volumes directly; that is, in a single step using an equation of the form $F = (V,L)$. The highway/transit network evaluation model, however, is an explicit consideration of both the supply and demand functions (i.e., $S(V,T)$ and $D(L,A)$).

PURPOSE OF THE MODEL

The model presented here is designed as a sketch planning tool in that it enables the transportation planner to screen easily a wide variety of transit hardware systems and operating policies. The product of the model consists of a set of alternative public transit systems which are worthy of further detailed study. The advantage of such a process is that a wider variety of system options may be considered initially since the substantial portion of the initial screening is done by the model.

The model is based on two hypotheses:

1. The level of service provided by a public transit system improves as the demand increases because of lower vehicle headways (time lag between vehicles) and the potential use of higher performance hardware systems.

2. The level of service provided by the private automobile, as indicated by average trip speed, has remained relatively constant in contrast to the historical deterioration of transit service.

Both of these hypotheses are examined in the following sections via the model's data requirements, and the model's philosophy is developed in the process.

DATA REQUIREMENTS

The model has three basic inputs. The first describes the potential transportation network. The second describes the characteristics of the proposed transit system and the characteristics of the existing highway/automobile system, and the third describes the size and orientation of the demand for travel irrespective of mode.

Template Network

The template network required by the model is a link-and-node representation of all the possible route alignments in the study area for both automobile and transit. The links in the network may represent all the existing and proposed roadways or just the major transportation corridors, depending on the level of detail desired. Since all possible facilities both existing and proposed must be included in the network specification, the problem becomes one of link elimination rather than link addition. Although not a rigid model requirement, it is convenient to define a common highway/transit network since the result of the model is a selective link-by-link specification of recommended transit service.

The Supply Function

Techniques for specifying the supply function for transportation facilities have in the past received very little attention. Only recently have efforts been made to define concisely (quantitatively) the quality of transportation available as a function of the level of service provided.

One of the first explicit treatments of the transit supply function was by Rea (2,3). His basic hypothesis was that

The Highway/Transit Network Evaluation and Planning Tool: A Policy Sensitive Model

by Bradley T. Hargroves[*]

the level of service provided by a public transit system improves as the demand increases because of lower vehicle headways and the viable use of higher performance hardware systems (e.g., larger and/or faster vehicles). This necessarily assumes that an acceptable level of comfort is maintained on individual vehicles and that the total supply of public transit capacity is adequate.

In order to examine the concept advanced by Rea, it is advantageous to consider only a single type of transit—the standard passenger bus, operating at several different headways. In general, the level of service (L) is given by the supply function:

$$L = S(\ell, t, d, h, N)$$

where:

ℓ = trip length;

t = time on vehicle in motion;

d = average dwell time at intermediate stops;

h = headway between vehicles; and

N = other parameters relating to level of service.

Since, however, only the standard passenger bus is being considered, it is reasonable to assume that the level of service may be adequately represented by the overall travel speed. This assumption permits the supply function to be rewritten as (2):

$$L = \ell/[t + (h/2) + d].$$

Figure 1 depicts a graphical mapping of this hypothetical supply function. Since the ordinate of the graph is average trip speed, a change in the level of service corresponds to a change in vehicle headways. A simple extension of this concept could use any combination of level-of-service parameters as the independent variables. Thus each step on the graph would represent a change in headway and/or mode of transit.

GRAPH OF A HYPOTHETICAL SUPPLY FUNCTION

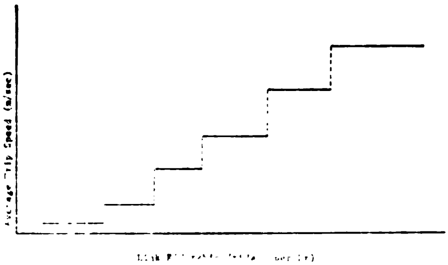

FIGURE 1

The real utility of this supply function framework, however, is that it can be used to illustrate the reasonable range of operation for a hypothetical bus at various headways. That is, at each service level (headway), the range of passenger flows is constrained on the low side by the economic viability of operation—the level of ridership necessary to cover operating cost. If ridership decreases below this level, it is usually necessary to cut service in order to maintain this break-even situation. The limit on the high side is determined by the physical capacity of the transit vehicle(s), in this case the bus. The capacity boundary may be defined as the seating capacity of the vehicle or the seating capacity plus some percentage of standees.

As an example, consider a transit route which is serviced by standard 60-seat buses at 10-minute headways. If all the vehicles are filled to the seated capacity, the physical capacity of the route is 360 passengers per hour. If the operating cost of each vehicle is $1.00 per mile and a fare of $0.05 per mile were charged, the break-even flow is at 120 passengers per hour.

Figure 2 shows the reasonable operating range for a hypothetical bus by connecting the viability and capacity points for the different vehicle headways. The locus of points defined by these boundaries and the service levels is designated as the service envelope (originally designated as a "service specification envelope" by Rea [2]).

A transportation planner may specify a particular transit policy by way of choosing to move up to the next service level (1) as soon as the next higher level becomes economically viable, (2) when he is forced to change because the capacity limit has been reached, or (3) at any flow level between the viability and capacity boundaries. The result is

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HYPOTHETICAL SERVICE ENVELOPE FOR BUS TRANSIT

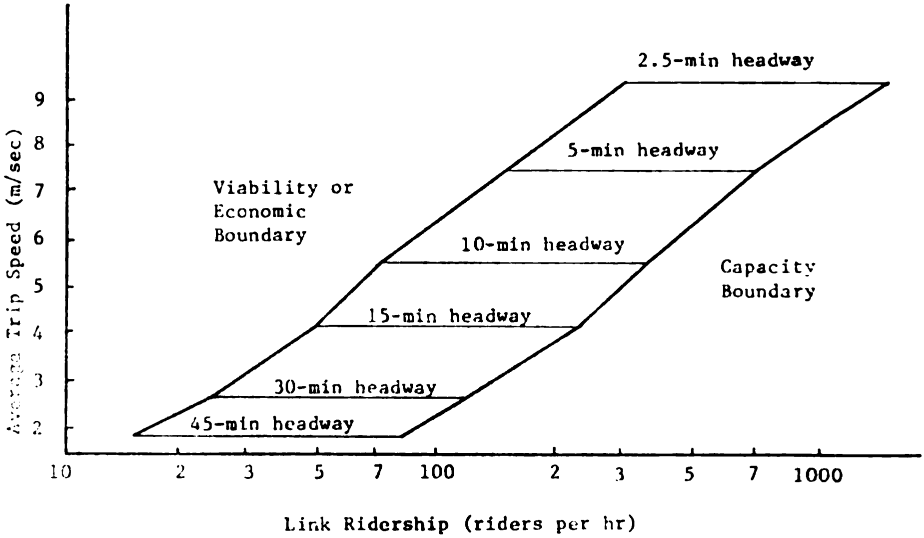

FIGURE 2

that the planner, given the service envelope for any particular technology, has the latitude of determining what level of service will be provided as a function of ridership.

The method for specifying the characteristics of the highway system is similar to that used for the transit case. The rationale is as follows. For urban highway systems, additional facilities are usually constructed when the level of service in some portion of the network falls below some prescribed value. These additional facilities are, in effect, incremental increases in the system's capacity, which in turn attract more usage and thus cause more facilities to be built. The result of this continuing cycle is that a relatively constant level of service is maintained for the highway mode. This constant level of service is represented as an average speed for the highway network. While this rationale may appear somewhat limiting, it does provide a framework for specifying the characteristics of the highway system. In addition, it reflects past policy wherein a high priority has been established for maintaining a high level of service for highway facilities. The model structure has the flexibility of allowing alternative highway supply functions if desired.

For the equilibrium approach used by the model, the supply functions for transit and for highways must be considered jointly. Figure 3 shows the two curves overlayed where the highway curve is approximated by the horizontal line defined at Q_{avg}. The superpositioning of the two curves illustrates the potential attractiveness of transit when transit volumes are high, even in this instance where an upper bound on highway capacity is not explicitly specified.

Travel Demand

The third and final input to the model describes the size and orientation of the total demand for travel that the transportation system must accommodate. In the most common situation, this demand array, or trip table, corresponds to the peak-hour, origin-destination (O-D) flows. The template network should be formulated preferably such that the origins and destinations are also network nodes. While this is not a require-

TRANSIT AND HIGHWAY SUPPLY FUNCTIONS

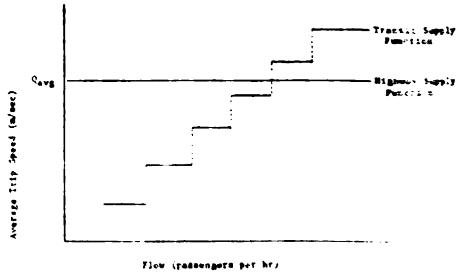

FIGURE 3

ment, it does reduce the complexity of the network.

THE HIGHWAY/TRANSIT ALGORITHM

The algorithm is essentially an iterative, capacity restraint, equilibrium technique wherein the transit and highway modes compete for usage. In the transit case, the O-D flows tend to concentrate in corridors of movement because the quality of service offered by transit improves as the flow levels increase. Thus, a trip maker may achieve a shorter trip time by traveling a less direct route in order to take advantage of the faster service provided in corridors with high flow levels. In essence, the various transit corridors compete with each other in order to acquire as high a service quality as possible. As a result, those links with high-quality transit service lure more drivers from their automobiles. Those links with low transit service then rely primarily on the automobile.

In the algorithm, equilibrium flow condition is achieved by the iterative procedure outlined in Figure 4. Initially, a first estimate of transit demand must be made. Then, using the transit supply function, the minimum time paths are determined and the transit demand is assigned to these paths. A comparison is made to check the compatibility of the transit volumes and transit supply on a link-by-link basis. If correspondence is not found on all links, the appropriate adjustments in transit service are made and the process recycles to Step 2.

If the transit flows and supply are compatible, the transit system definition is used to calculate the portion of transit usage (modal split). If the modal split is different from that previously specified, the algorithm recycles to Step 2; if the modal split is not different, the algorithm has reached convergence and is complete.

In order to estimate the portion of transit usage, a technique by Rassam et al. (4) was adapted. In its basic form, the method states that:

$$D_{im} = W_{im} D_i \qquad (1)$$

where:

D_{im} = share of trip makers at "i" on mode "m";

D_i = demand at node "i"; and

W_{im} = share of trip makers attracted to mode "m" at node "i".

Clearly, W_{im} is the parameter to be estimated (or predicted).

ALGORITHM FLOW CHART

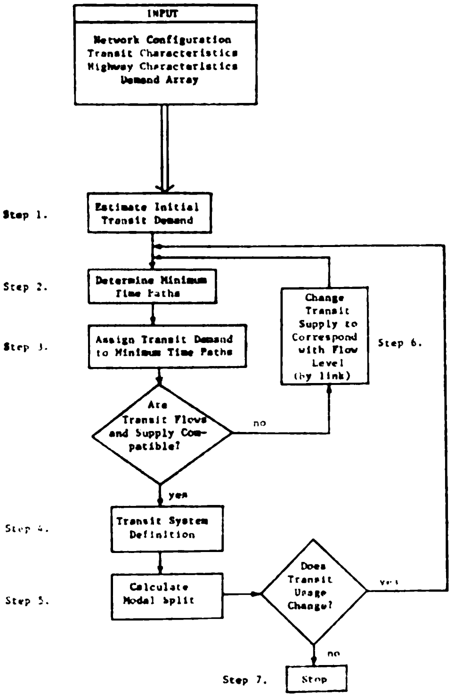

FIGURE 4

The relationship used to define W_{im} is:

$$W_{im} = \frac{\exp(-I_{im})}{\sum\limits_{K=1}^{n} \exp(-I_{ik})} \qquad (2)$$

where:

I_{ik} = impedance from i by mode k, $k = 1 \ldots m \ldots n$

$$I_{im} = \min_{p \epsilon P_m} \sum_{j \epsilon p} (d_j). \qquad (8)$$

The I_{im}'s are the minimum impedance paths of the network, in which

P_m = set of all paths from (origin) node i to the destination nodes by mode m;

p = a particular path within the set of all paths P_m;

$d_j = \alpha_j X_j$ = impedance of the jth trip component of a path P (i.e., impedance on link j of path P);

X_j = time (or cost) spent at the jth trip component (i.e., travel time); and

α_j = travel time coefficient associated with the jth trip component.

Since only two modes are being considered, the expression for W_{i1} becomes:

$$W_{i1} = \frac{\exp(-I_{i1})}{\exp(-I_{i1}) + \exp(-I_{i2})} \qquad (4)$$

where:

W_{i1} = the proportion of transit usage from i; and

I_{i2} and I_{i2} = the impedances of the transit and highway paths, respectively.

It is assumed that travel time alone will be an adequate measure of the impedance or relative disutility of the two possible modes. Obviously other variables, such as cost, comfort, and convenience, could be included, but in the interest of simplicity, they have been omitted in the work to date.

COMMENTS ON THE MODEL

The final output of the model is not necessarily an operational transit system because the model reaches the equilibrium condition by considering exclusively the status of individual links. Since an operational transit system must consist of an integrated set of routes and schedules, some refinement may be required. Tests to date, however, show that relatively little adjustment is required to produce an acceptable route structure.

In addition, it is assumed in the model that the link volumes are such that the transit level of service is not adversely affected by the volume of automobile traffic. For transit systems that operate on exclusive rights-of-way (such as rail facilities and exclusive bus lanes) this assumption is valid. Where volumes on shared facilities are sufficient to adversely affect the level of transit service, such as those in the central business areas, transit speeds could be specified at a lower level.

Finally, due to the internal structure of the model, the transit system prescribed is not necessarily an optimal solution. This is due to the step structure of the transit supply function and the fact that in the algorithm, the adjustment of the link's status trails rather than leads the trip assignment step. Preliminary tests, however, do show that that model does have the capacity of eliminating less desirable transit systems and probably produces a near optimal solution for a given set of transit-operating policies.

EXPERIMENTAL RESULTS

In order to test the performance and sensitivity of the model, a computer program was written in FORTRAN and run at The Pennsylvania State University. The test was specifically designed to evaluate the model's responsiveness to changes in the supply functions for both transit and highway modes and to changes in the demand array.

The test data consisted of several alternative bus operating policies (e.g., the viability and capacity boundaries). The template network was an abstraction of the highway system for York, Pennsylvania. It consisted of 84 paired links and 30 nodes, 23 of which were origin-destination nodes. The total demand array was based on the 1963 travel patterns in the same area.

By way of varying the several input parameters, several important points evolved. First with respect to transit, an operating policy which schedules additional vehicles when their operating costs can be met is best from both the consumer's and transit industry's standpoint. The general transit network is more accessible to all points in the system, average travel speeds are higher, and transit profits are greater.

From the standpoint of the auto users, the same policy is also best. Since larger numbers of travelers are using transit, the highways will be less congested while the quality of transit is kept at a high level. Also, if the existing transit usage is fairly low relative to auto usage and the total demand for travel increases, transit can attract a large portion of the increased demand if attractive transit service is available.

Finally, if the general quality of highway service is improved and transit policy dictates no increase in the quality of transit service, transit patronage will obviously degenerate. With the current model calibration, the indication is that a 25 percent increase in highway speeds will result in a 56 percent decrease in transit usage.

DIRECTIONS FOR FUTURE RESEARCH

To date, substantial progress has been made in the development of the supply function concept in application to transit planning. While the potential value of this tool has been amply demonstrated here and elsewhere (2, 3), there remains a number of promising avenues for further study.

The first area for future work involves the specification of the highway characteristics. The present version of the model assumes that the highway service will remain relatively constant in the long run. In the short run, however, highway service obviously declines with concentration of usage. It would be useful, then, to recognize the short-run variations in highway service and, in turn, to allow those variations to affect minimum time path selections and modal choice decisions. The most rea-

sonable approach would be to incorporate any one of the several capacity-restrained traffic assignment models into the existing highway/transit model. Such an increment in the model's development may be expected to have a significant effect on the algorithm's convergence to an equilibrium solution.

A second area that requires refinement is the transit route synthesis. The final output of the existing model is a link-by-link specification of vehicle type and operating headways. At present these must be manually transformed into a set of transit routes and schedules. Implications from the work done to date indicate that only minor adjustments are likely to be necessary. Nevertheless a significant improvement in the model would result from the inclusion of a scheduling algorithm to insure a reasonable set of routes and schedules as part of the output.

Another potentially useful facility of the model is to expand the existing transit service constraint mechanism. The model currently accepts such individual link constraints as "no rapid transit mode may exist on Main Street" or "bus service on North Street must run at least hourly," but constraints on the entire system cannot be accommodated directly. One such entire system constraint might be to limit the model to consider a fixed or upper bound on the total number of transit vehicles available. This facility would conform to common limitation placed on most transit operations in a real-world planning context.

Finally, a number of additional but less immediate capabilities could be added on to the model's present capabilities. One possibility is to link the model to a cathode ray tube for visual display of the output. Such pictorial, dynamic presentation could well be an important feature in selling the tool to planners. In addition there is the potential of using this feature for public presentation of alternative transit systems.

Other possible model additions might include such features as environmental impact or energy consumption submodels. While the present model structure is not easily adaptable to multiple objective programming, features such as these offer a wide variety of exploratory potential.

CONCLUSION

In an era when transit ridership is such a paramount issue, it is important to investigate the interrelationships of those factors which determine the level of demand for public transit. In this context, the highway/transit model provides a useful concept for examining the implications of alternative transit policies in a transportation environment which is heavily dominated by the private automobile. The assumptions most basic to the model are (1) that the quality of service provided by transit is a function of increasing transit ridership, and (2) that the level of service provided by the private automobile has been maintained at a relatively high level.

As a heuristic planning device the highway/transit model fills a critical gap in the current transportation modeling process. While only the long-run equilibrium has been addressed, the important implication of the model is that transit ridership can be increased via consumer-oriented transit policies. To this end the highway/transit model provides a mechanism for evaluating the impact of these policies.

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