A Method of Network Evaluation Using the Output of the Traffic Assignment Process

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•THE objective of the research underlying the method described in this paper has been to discover and develop a means of network evaluation that will help to determine just who benefits or loses from a particular network change (1). A further motivation has been to determine quantitatively how much each group gains or loses. One particular difficulty with existing methods of evaluation is the need to assume that the level of demand remains fixed between alternative networks, that is, that demand is unaffected by changes in the transportation network or in the operation of it (2, 3). Consequently, the research has entailed looking for a method that will help determine the value of trips apparently diverted, generated, or eliminated by alterations to the network or to the means of operating it.

What has been found is a way of looking at network flows that will permit the determination of the net gain or loss accruing from them, no matter how demand differs between networks. In this paper, the method will first be presented with the type of demand model to which it appears to be best suited. Then, possible ways of using the method with existing means of estimating travel demand will be shown.

Although the method can be used to compute the net user benefit accruing from flows over a given network, it is most useful in comparing alternative networks on the basis of the difference in net user benefits accruing from them. It requires interzonal traffic volumes and interzonal separations from each alternative network. In some cases, as will be shown, it needs interzonal travel demand as a function of interzonal separation-interzonal travel demand functions.

In most cases, the interzonal separations should be those which it is assumed are experienced by users of the network. The variable used to describe interzonal separation can be travel time, travel cost including value of time, or some other such measure. It is important to note, however, that the resulting evaluation will be only as comprehensive as this measure of interzonal separation is.

It should also be recognized that the user benefits computed using the method are intended to be one dimension in a larger framework of network evaluation. Predicted user benefits must be combined with estimates of construction and maintenance cost in network comparisons. Individual link volumes need to be assessed for congestion, overcapacity, and traffic noise. Other data on other network attributes must also be examined. Still, user benefits are vital to any network evaluation, if not its most important element.

UNDERLYING ASSUMPTIONS AND THE BASIC ECONOMIC RATIONALE

It is first assumed that the markets for travel between zones in urban areas can be expressed in terms of demand and supply curves. Figure 1 shows a demand and a supply curve, each with its normally assumed shape. The demand curve is a plot of the prices of interzonal travel vs the number of trips that would be taken between the zones at each price. It is thus a plot of what people are willing to pay to travel between zones.

The supply curve defines what the producer would have to be offered in terms of a unit price in order to be induced to output a given number of units. Since the producer here is just the impersonal transportation network, the supply curve is a plot of what

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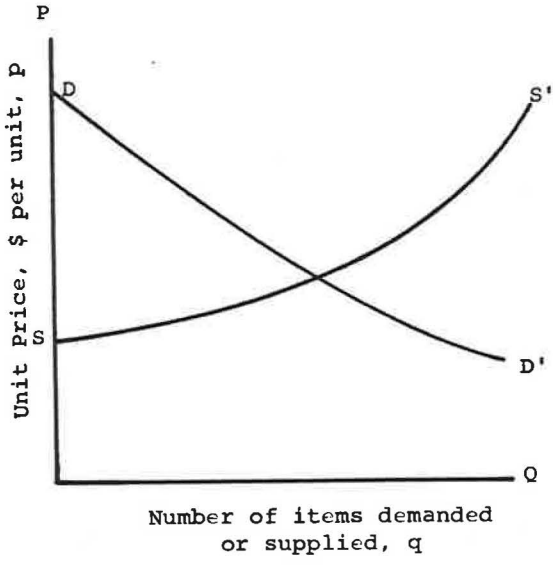
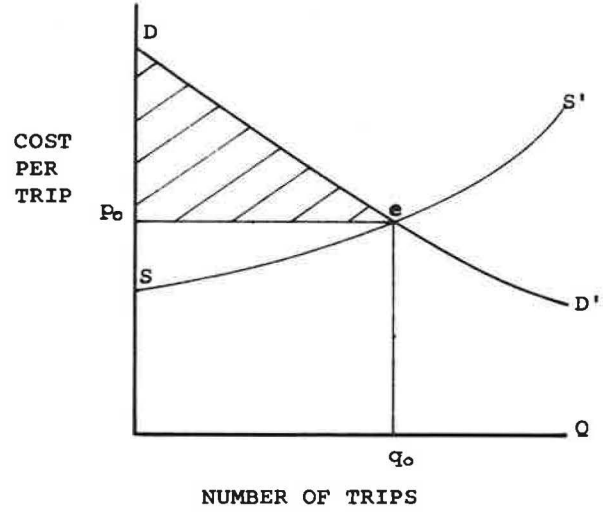


Figure 1. Supply and demand curves.



TRAVEL FROM ZONE 1 TO ZONE 2

D-D' = plot of what potential travelers are willing to pay

S-S' = cost per trip as function of number of trips undertaken

p_o = equilibrium cost = what travelers are required to pay; q_o = equilibrium number of trips

area D-e-p_o = difference between what travelers are willing to pay and what they have to pay = traveler's or consumer's surplus

Figure 2. Equilibrium of supply and demand for interzonal travel and determination of user benefit from interzonal travel.

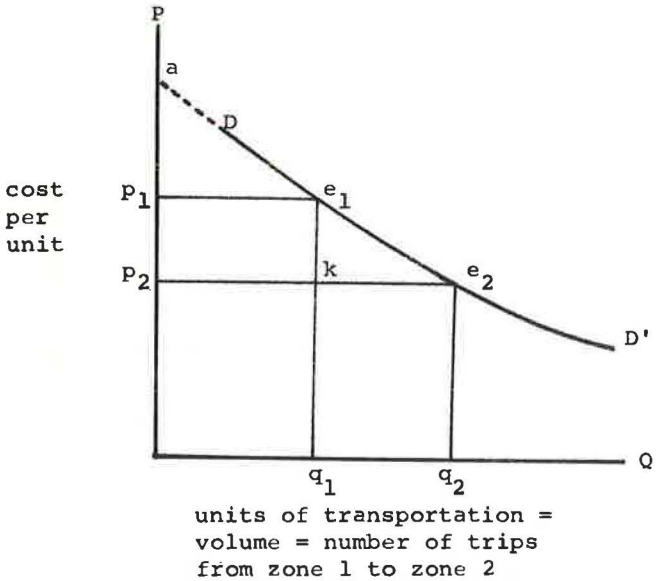


Figure 3. User benefit accruing to travel between two zones from an improvement to the transportation system.

people have to pay to travel between two zones as a function of the number of trips taken between the zones. The terms "price," "cost," "accessibility," and "separation" as used in this paper to define the cost of travel between two zones are intended to be synonymous. Thus, the supply curve is directly analogous to a volume-travel time or a volume-travel cost capacity restraint function but for travel between zones rather than over a single link.

An equilibrium of supply and demand is defined by the intersection of the curves of supply and demand for travel between two given zones. The equilibrium thus occurs when the cost (price, separation, etc.) of travel between the two zones just equals what the last traveler (as determined by the demand curve) is willing to pay to make the trip. Therefore, the interzonal volume and the interzonal separation are the coordinates of a supply-demand equilibrium point. Figure 2 shows just such an interzonal equilibrium. Note that the separation axis is in terms of the unit cost of travel. The unit cost is defined as the sum of the out-of-pocket expenses and the value of the time consumed in making the trip. Although interzonal separation could be expressed in terms of travel time or some other measure, the foregoing definition will be assumed in the remainder of this paper unless otherwise specified.

The Measure of Benefit-Consumer Surplus

Once the equilibrium point is determined, the amount of user benefit accruing from travel between the two zones can be computed. It should be recalled that the demand curve is a plot of what potential travelers are willing to pay to travel between the zones. The equilibrium price or separation is what the travelers are compelled to pay to make the trip. The difference between what these travelers are willing to pay, the demand curve, and what they have to pay, the equilibrium price, is defined as the benefit that accrues to these travelers as a result of their taking the trip. This measure of user benefit is thus synonymous with consumer surplus. Figure 2 graphically displays this concept of user benefit.

Consumer surplus was introduced as a measure of value by the British economist, Alfred Marshall, in the late nineteenth century (4). Since that time, controversies have arisen between economists as to the conditions and validity of its use, but these controversies do not invalidate its use in the present case and are too varied and involved to be summarized here (5). Consumer surplus is probably most clearly presented as a measure of the amount of user benefit accruing from improvements in the transportation system by Mohring and Harwitz (6). Figure 3 shows the composition of user benefit in this context. The initial cost and volume of travel, e.g., between two zones, are p_1 and q_1, respectively. An improvement is made to the system that results in a lower cost of travel between the two zones, p_2, and a consequent increase in travel to volume q_2. The benefit to the initial users is the lessening of the total cost of q_1 units of travel from p_1q_1 to p_2q_2, or the area $p_1e_1kp_2$. The net benefit accruing to the additional trips taken after the improvement, q_2-q_1, is defined by the area e_1e_2k. It is the difference between what

the new travelers are willing to pay, as defined by the demand curve, D-D', and what they have to pay, p_2. (The new trips are shown by Mohring and Harwitz to be due to the substitution of transportation-intensive goods and services for other goods and services.) The total gain is thus equal to area $p_1e_1e_2p_2$. This gain is merely the difference in consumer surplus before and after the improvement, that is, area ae_2p_2 minus area ae_1p_1. Mohring and Harwitz further show that this measure of gain gives a close estimate of the total economic benefit from an improvement in the transportation facilities, provided that (a) transportation comprises a reasonably small proportion of the average consumer's budget and (b) business firms are reasonably "competitive" in the strict sense defined by economic theory (6). (A competitive firm in this sense is one which has enough competitors that it alone cannot arbitrarily set the prices of the goods it produces.)

Thus, the total benefit from transportation improvements may be closely approximated by user benefit and user benefit is defined by the resultant change in consumer surplus.

Supply Curves for Travel Over Networks

In order that supply-demand concepts may be applied to estimation of the benefit accruing from transportation improvements, it is necessary to examine the supply function for travel over a network. The supply curve is normally used to indicate what the producer of the item being supplied would have to be offered in terms of a unit price to induce him to produce another unit of the item. Since it is also normally assumed that he wishes to recover just whatever marginal increase occurs in his total costs due to producing the extra unit, his supply or offer curve is assumed to be his marginal cost curve.

In the case of the interzonal travel market, the basic trip-producing unit is assumed to be the link. The supply curve is a plot of the average unit cost of travel (as perceived by the traveler) over the link as a function of the number of vehicles using the link in a given time period. Marginal cost is not used here because it is average cost which the user perceives. In other words, it is assumed that the user does not take into account the changes in the costs to other users caused by his presence on the link; he is only interested in the cost to himself. The following formulas may help to clarify the difference between marginal and average costs by showing their respective relationships to total cost (7):

$$AC = \frac{TC}{q}$$

$$MC = \frac{dTC}{dq} = \text{slope of total cost curve at } q$$
$$= \text{change in total cost caused by addition of one more vehicle}$$

where

TC = total cost of q trips over a given link, \$;
AC = average cost per trip, \$/trip; and
MC = marginal cost of a given trip, \$/trip.

The shape of the supply curve for trips over a link thus depends on the physical characteristics of the link and the interactions between the vehicles traveling over it. A supply curve for an entire interzonal trip over a given route may be derived merely by adding up the supply curves for each of the links comprising the route, such as the minimum path between the zones, as shown in Figure 4.

The supply curve for travel between two zones is actually made up of portions of the supply curves for each of several alternative routes, as shown in Figure 5. Figure 5 shows that as congestion builds up on any one route, a more circuitous route may become the minimum path. Also, the supply curve as shown implicitly assumes a certain level of network loading, that is, trips between other zone pairs over the same links. In the example of Figure 5, only link 4-2 carries traffic between another zone pair, zones 3 and 2. The contribution of this traffic to the curve for path 1-4-2 and hence to the supply curve for travel between zones 1 and 2 is shown by the dashed lines.

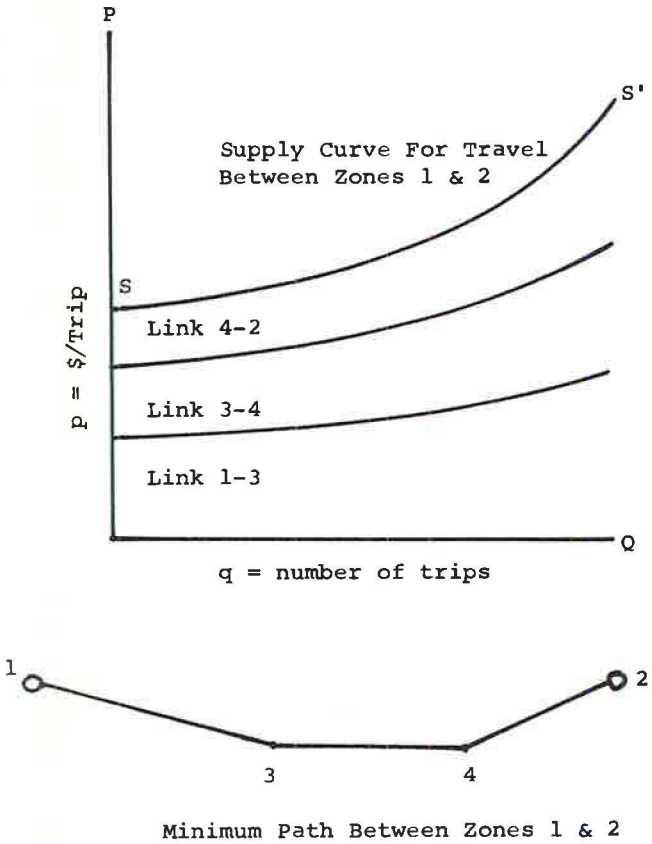


Figure 4. Obtaining interzonal supply curves.

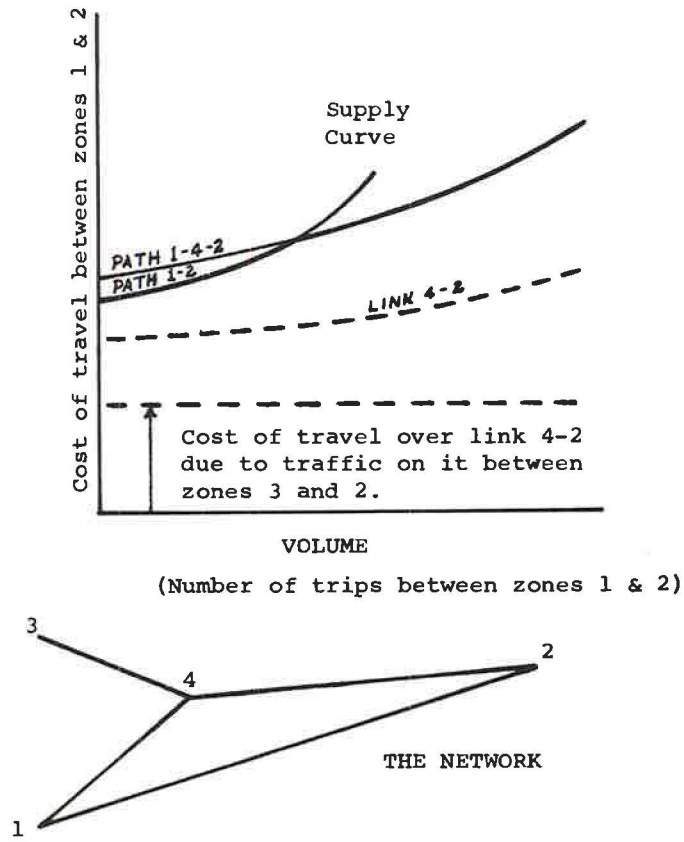


Figure 5. Make-up of interzonal supply curves.

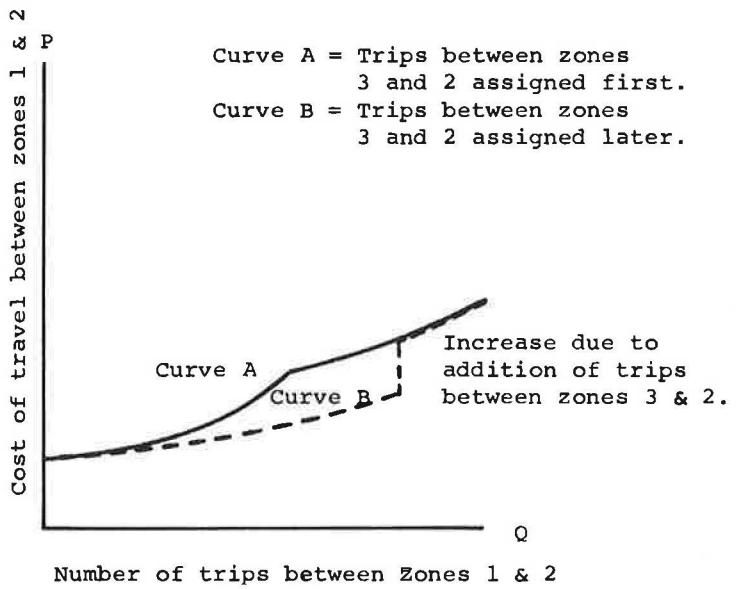


Figure 6. Supply curve differences due to different loading sequences.

Thus the loading of traffic between zone pairs in different sequences may produce different supply curves for travel between any one given pair of zones. Figure 6 illustrates two such possibilities for the travel between zones 1 and 2. Note that as soon as travel between zones 3 and 2 is added to the network, that is, the network is more completely loaded, the alternative supply curves get closer together (in this case, they coincide). This implies that the equilibrium interzonal travel times are consistent on a network with all trips assigned to it no matter what the loading sequence happened to be. It is important to note this consistency because it implies that the evaluations produced by the method outlined in this paper are also consistent no matter what the loading sequence.

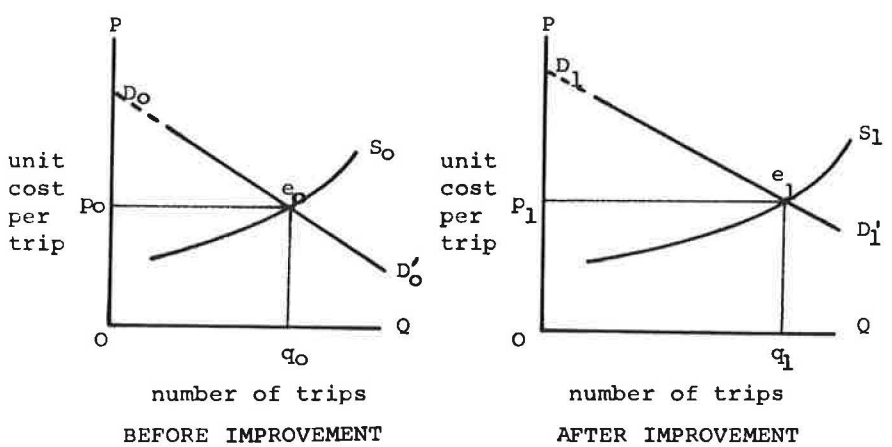
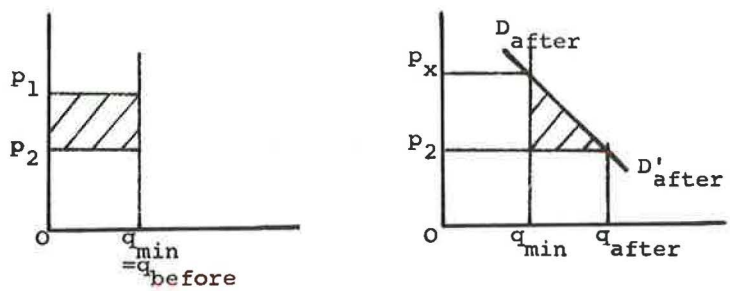


Figure 7. Computation of benefit accruing to travel between two zones due to an improvement in the transportation system—idealized version.

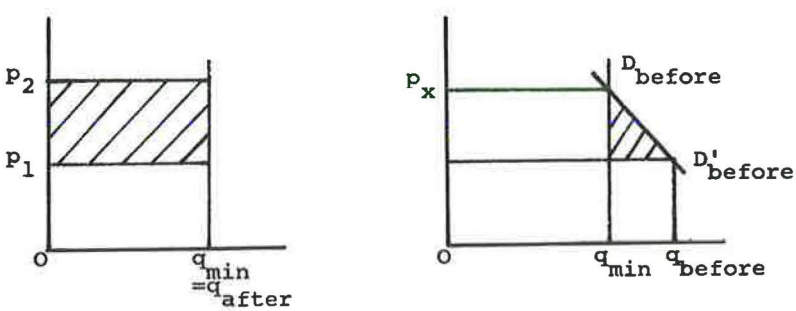
THE METHOD—AN IDEALIZED VERSION

The method of evaluating network changes consists of merely summing the difference in consumer surplus accruing from interzonal travel, as outlined in the previous section, over all zone pairs. The idealized version outlined in this section requires a demand function for travel between each pair of zones over each network. Compuation of the difference in benefit between networks would proceed as shown in Figure 7. Curves D_0 - D_0' and D_1 - D_1' are the two required demand curves for travel between zones 1 and 2 over the initial and improved networks, respectively. Hence, the benefit over

CASE I. GAIN



CASE II. LOSS



p_1 = interzonal price before change in network

p_2 = interzonal price after change in network

q_{min} = number of interzonal trips taken both before and after the network change = $\min(q_{before}, q_{after})$

q_{before} = number of trips taken between zones concerned before change in network

q_{after} = number of trips taken between zones concerned after change in network

p_x = price coordinate of point on demand curve at q_{min}

Figure 8. A more practical form of the idealized version.

each network is defined by areas $D_0e_0p_0$ and $D_1e_1p_1$. The change in benefit due to the improvement is the difference between the two areas, $D_1e_1p_1$ minus $D_0e_0p_0$. This quantity, summed over all zone pairs, would give the total benefit due to the improvement.

It would also be necessary to sum the evaluation over all time periods for which the demand pattern is assumed to be significantly different. The division of time periods depends on the time period on which the traffic assignment is based. For example, if the traffic assignment is an hourly one, the relevant time periods between which the pattern of demand changes might be the morning peak, evening peak, and off-peak; if the traffic assignment is performed on an ADT basis, the time periods of differing demand patterns might be the average annual weekday and the average annual weekend day.

The idealized version of the method in the form described has the disadvantage of requiring the computation of areas under the demand curve near the vertical axis. In many cases the demand curve is asymptotic to the vertical axis or is undefined in this region. The area under such a curve is therefore infinite or undefined. It appears most reasonable, therefore, to compute the change in benefit, in consumer surplus, in the manner illustrated in Figure 8.

For those interzonal trips, q_{min}, taken both before and after the network change being evaluated, the change in benefit is equal to the change in price, $p_2 - p_1$; the sign of the quantity $p_2 - p_1$ will determine whether a gain or a loss has been incurred for these trips. For those trips added or deleted (or diverted) by the network change, the change in benefit is equal to the area under the demand curve and above the lower equilibrium trip price. When a gain—a reduction in user costs—has been incurred, the area concerned is that under the interzonal demand curve for travel after the network change and above the interzonal trip cost or price on the network after the network change and above the interzonal trip costs or price on the network after the change. Conversely, when a loss—or an increase in trip price—is incurred, the area concerned is that under the interzonal demand curve for travel before the change and above the equilibrium interzonal trip price on the network before the change. For each case, gain or loss, the total change in user benefit accruing to the trips between the zones concerned is the sum of the benefit for q_{min} and for q_{after} or q_{before} minus q_{min}—the sum of the cross-hatched areas in the left and right figures for each case.

It should be noted that p_x is the trip price determined by the intersection of the demand curve with a vertical line drawn at q_{min}. Because the interzonal demand curve may shift—change position and shape—due to the network change, p_x is not necessarily equal to p_1 in Case I nor to p_2 in Case II.

The difficulty with the idealized version is the requirement of a demand function for each zone pair for each network. Demand functions are not necessarily the same for the same zone pairs for different networks; if they were the same, the benefit due to a network improvement could be directly computed from only the interzonal volumes and interzonal separations for the initial and improved networks. This computation and the possibilities for its use will be described in the next section. Nevertheless, interzonal travel demand functions are being formulated by other investigators, so it appears it may be possible in the near future to use the idealized version (9, 10).

USE OF THE METHOD WITH CURRENT MEANS OF TRAVEL ESTIMATION

Interzonal Trips as the Basic Commodity Demanded

It is possible to use the method described in this paper with information from current means of travel estimation. Two modes of use are described and both provide approximations of the results that would be obtained from the idealized version. The first of these modes still utilizes the concept of demand on a specific zone-to-zone basis. Its major drawback is that it requires the assumption that the demand curve for travel between any zone pair remains fixed between alternative networks. The reason for this requirement being a serious drawback can be more easily presented after a description of this version of the method is given.

The major advantage of this version is its ease of computation when used with current means of travel estimation. The version involves approximation of enough of a

fixed demand curve to give a measure of the difference in the user benefits accruing over two alternative networks from travel between a given pair of zones. The ability to make such an approximation requires the assumption that the demand curve for travel between two zones is the same over each of the networks being compared. Therefore, since the equilibrium point falls on the demand curve, the equilibrium points for two different networks for travel between the same two zones would fall on the same demand curve. A line segment drawn between these two points approximates that portion of the demand curve, as shown in Figure 9.

Figure 10 shows the six possible cases of the relative orientation of the two equilibrium points. It also shows that the change in user benefit accruing from network 2 as compared to network 1 may always be computed by the following formula:

$$B = q_1 \cdot (p_1 - p_2) + \tfrac{1}{2}(q_2 - q_1) \cdot (p_1 - p_2)$$
$$= \tfrac{1}{2}(p_1 - p_2)(q_1 + q_2)$$

where

B = change, or increment, in user benefit;
q_1 = equilibrium number of trips over network 1 between the given zones;
q_2 = same as q_1 but for network 2;
p_1 = equilibrium separation or price of travel between the given zones over network 1; and
p_2 = same as p_1 but for network 2.

As with the idealized version, the sum of the incremental benefits over all zone pairs will give the total user benefit accruing from one network when compared with another for the time period concerned. It is also necessary to sum over those time periods between which demand patterns differ significantly.

The ease of data acquisition and computation makes this version appear highly desirable. The following analysis is intended to illustrate why demand functions for many, if not most, trips are not the same, however, before and after a given improvement.

Demand curves such as those illustrated in this paper show the number of units of a certain commodity that will be consumed as a function of the price of that commodity.

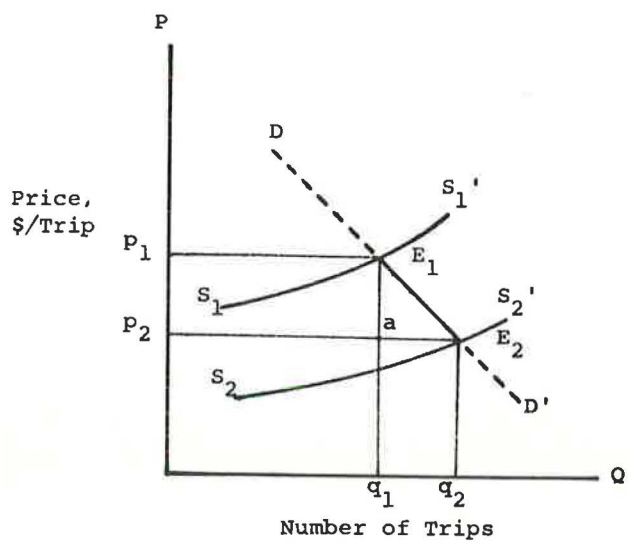


Figure 9. Approximation of user benefit from travel between two zones using an assumed fixed demand curve.

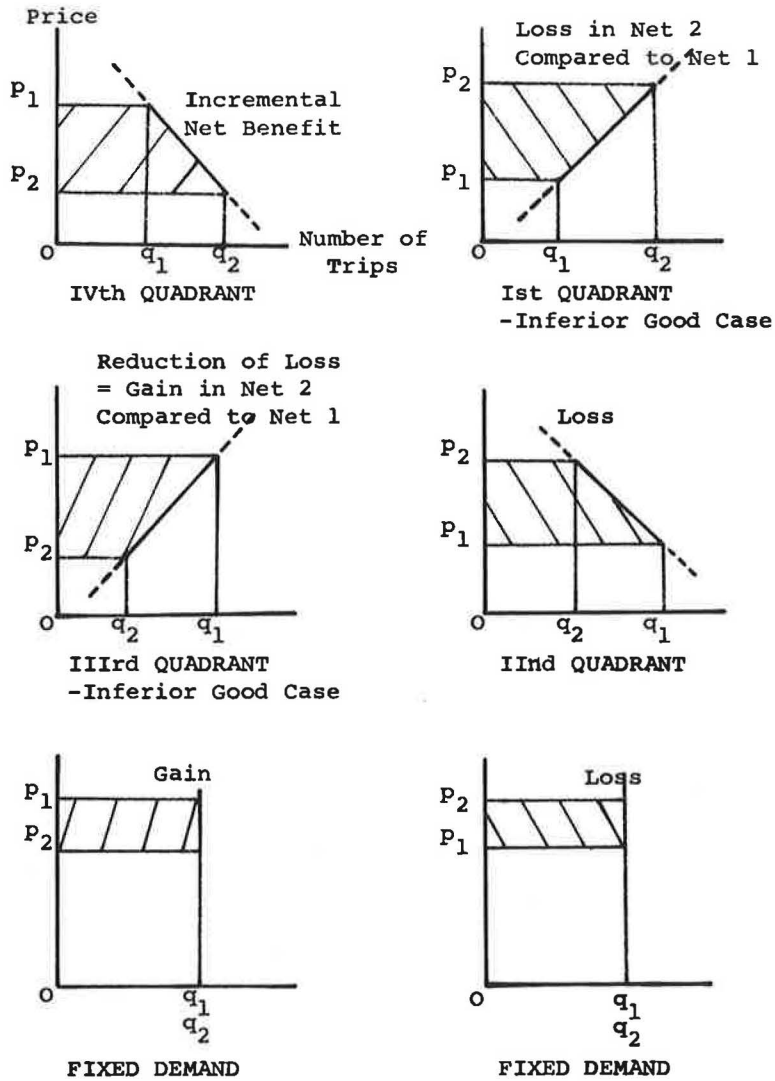


Figure 10. The six cases of "gain" and "loss" with a fixed demand curve.

However, the number of units that consumers will purchase depends not only on the price of the commodity itself but on the prices of other commodities as well, particularly those that can be substituted for the commodity in question (11). For example, if the price of coffee goes down far enough, tea drinkers may drink a lot less tea because they will substitute coffee for it even though the price of tea remains the same. This problem can be overcome in many economic analyses by assuming that the prices of all other commodities except the one in question remain constant. However, an improvement in a network usually affects not only the price of the trip between a given pair of zones but also the prices of trips between these and other zones. As will be

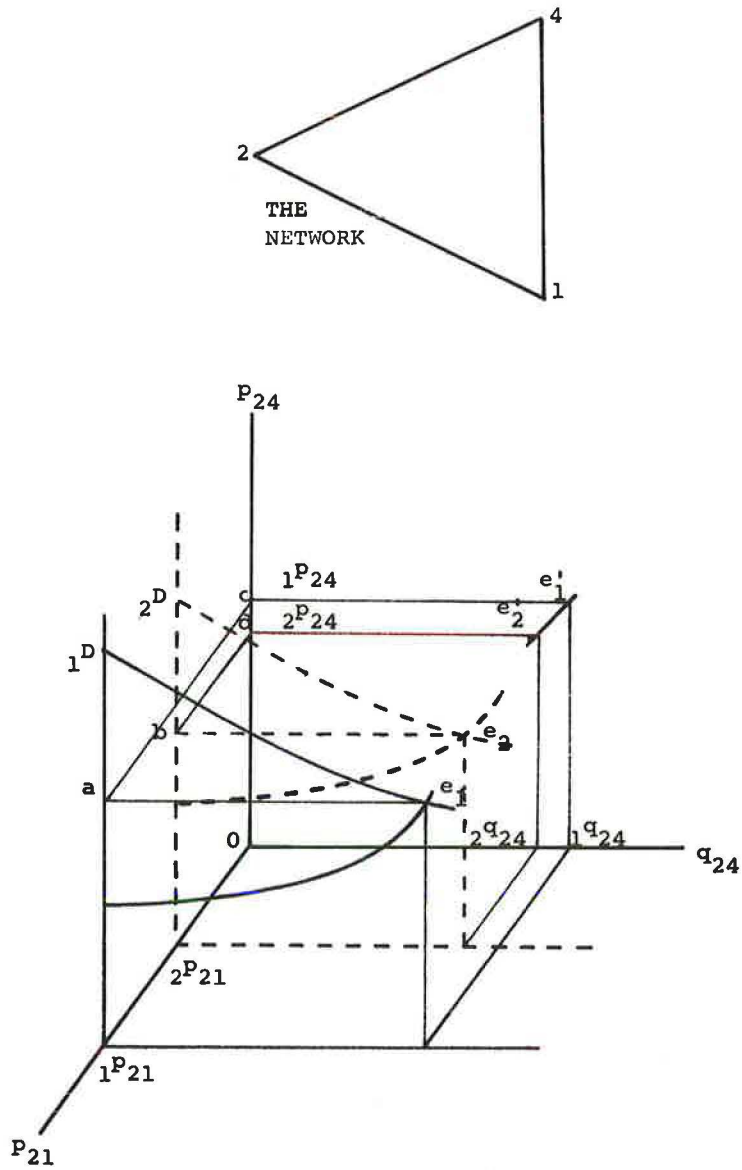


Figure 11. Change in consumer surplus accruing to trips from zone 2 to zone 4 due to change in cost of travel from zone 2 to zone 1.

shown, the changes in prices of trips from the same origin zone as the one in question may well cause the demand curve for the trips in question to shift, thus raising doubts about this version of the method.

The following example refers to the very simple network shown at the top of Figure 11. Travel from zone 2 to zone 4 is under consideration. An improvement is made to link 2-1, shortening the travel time between zones 2 and 1. With regard to individual link supply curves, only that for link 2-1 is changed. This will affect the supply curves of all interzonal trips for which link 2-1 forms a part of the interzonal route. It appears that only the supply curve for trips from zone 2 to zone 1 will be affected. Consequently, a redistribution of trips caused by the improvement and resulting in a change in trips

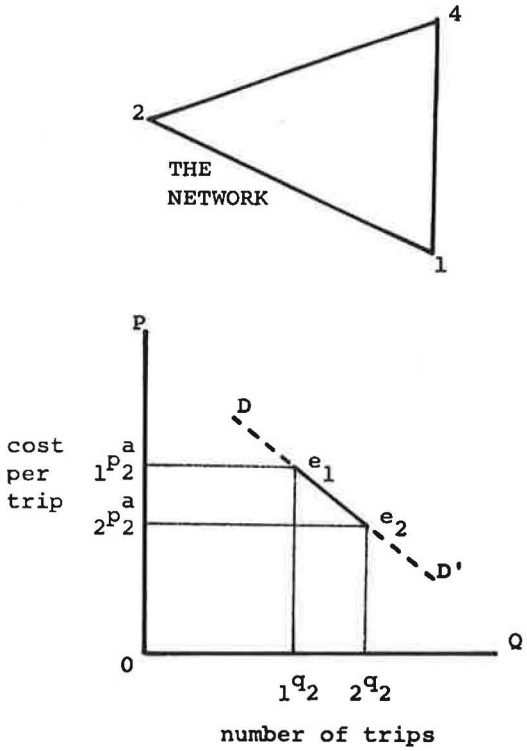


Figure 12. Computation of net benefit accruing from all trips of given purpose originating in zone 2.

from zone 2 to zone 4 must be due to a shift in the demand curve, not in the supply function, since the supply function for link 2-4 remains unchanged. It should be noted that this very simple example merely illustrates a point. In virtually every real-world case, one would expect the supply curves to shift due to differences in the pattern of network loading caused by the differences in networks.

The illustration does seem plausible for trips of certain purposes, particularly shopping and social-recreational. Such activities could be engaged in by people from zone 2 at either zones 1 or 4. If it becomes less expensive to go to zone 1 due to an improvement in link 2-1, it is reasonable to expect some of the trips being made from 2 to 4 for these purposes to be diverted to zone 1, assuming the activities at 4 and 1 are equally desirable on other counts.

The lower portion of Figure 11 illustrates the effect of such substitution on the computation of the change in benefit accruing from trips between zones 2 and 4 due to the improvement. Travel demand between zones 2 and 4 is represented in three dimensions instead of two—the number of trips, q_{24}, the price of travel between zone 2 and 4, p_{24}, and the price of travel between zones 2 and 1, p_{21}. The demand curve for travel between zones 2 and 4 before the improvement is the solid line, $_1D$ - $_1D'$, shown at $_1p_{21}$, the price of travel between zones 2 and 1 before the improvement. After the improvement, the price of travel between zones 2 and 1 falls to $_2p_{21}$, causing fewer trips to be demanded between zones 2 and 4 at each level of price, p_{24}. The new, shifted demand curve is represented by the dashed line $_2D$ - $_2D'$. Note that the supply curve for trips between zones 2 and 4 is the same both before and after the improvement. The actual change in consumer surplus (or benefit) is area $_2De_2b$ minus area $_1De_1a$, which appears to be a reduction.

The simplified version of the method results in a reduction in benefit defined by area $ce_1'e_2'd$ in plane q_{24} - p_{24}. Although the change in benefit indicated by the simplified version has the correct sign (negative), there is no guarantee of equality between the quantities of benefit change computed by the two versions; area $ce_1'e_2'd$ is not necessarily equal to area $_2De_2b$ minus area $_1De_1a$.

The magnitude of the error cannot be determined until more is known about the actual shapes and shifts of the interzonal travel demand curves. It is also unclear at this point how well present trip generation and distribution models reproduce changes in interzonal travel patterns induced by network improvements. Any use of the simplified version of the method with present travel estimation techniques should be done with clear recognition of these limitations.

All Trips From a Given Origin Zone as One Commodity

The second version of the method for use with data from current means of travel estimation requires a somewhat different way of looking at travel. In this case all trips of a given purpose from a given origin zone are considered to be one commodity. This point of view differs from that of the previously described versions in which all trips

of a given purpose from a given origin zone to a given destination zone were considered to be one commodity.

Figure 12 illustrates this new point of view. The example is very similar to that of Figure 3. The primary difference is that the price is now the weighted average of all the trips (of the purpose concerned) from the given origin zone. For the very simple network shown, the average price is computed as follows:

$$ {}_1p_2^{\,a} = \frac{{}_1p_{24} \cdot {}_1q_{24} + {}_1p_{21} \cdot {}_1q_{21}}{{}_1q_{24} + {}_1q_{21}} $$

where

${}_1p_2^{\,a}$ = average price of trip from zone 2 over network 1;
${}_1p_{24}$ = price of trip from zone 2 to zone 4 over network 1; and
${}_1q_{24}$ = number of trips between zones 2 and 4 over network 1.

The general formula for average price is, therefore,

$$ {}_kp_i^{\,a} = \frac{\sum_j {}_kp_{ij} \cdot {}_kq_{ij}}{\sum_j {}_kq_{ij}} $$

where

${}_kp_i^{\,a}$ = average price of trip from zone i over network k;

${}_kp_{ij}$ = price of trip from zone i to zone j over network k; and
${}_kq_{ij}$ = number of trips from zone i to zone j over network k.

The difference in benefit accruing from two alternative networks may now be computed as shown in Figure 3. Using the terminology of Figure 11, the computation is as follows:

$$ {}_{21}B_2 = \tfrac{1}{2}\left({}_2q_2 + {}_1q_2\right)\left({}_1p_2^{\,a} - {}_2p_2^{\,a}\right) $$

where

${}_{21}B_2$ = net gain to trips from zone 2 on network 2 as compared to network 1;
${}_1q_2$ = total trips originating from zone 2 over network 1; and
${}_1p_2^{\,a}$ = as described above.

The total net gain accruing from travel is the sum of the gains from each origin zone,

$$ {}_{21}B_{Total} = \sum_i {}_{21}B_i $$

where

${}_{21}B_{Total}$ = total gain from net 2 as compared to net 1; and
${}_{21}B_i$ = gain to trips from origin zone i for net 2 as compared to net 1.

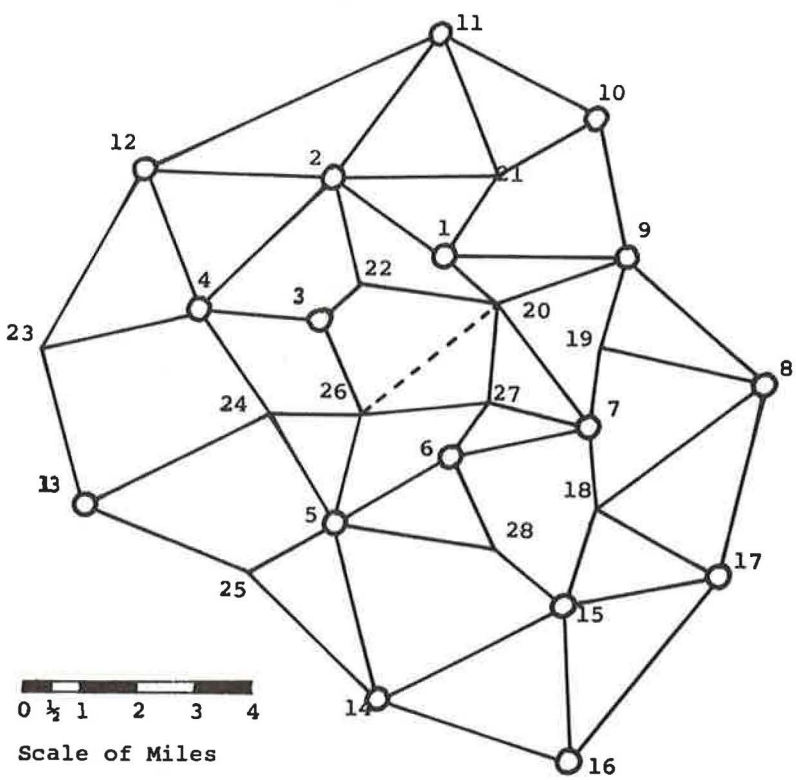
The point of view of the travel market represented in this version of the method means that changing the prices of trips that are potential substitutes for the one concerned is no longer a source of error. The shifting of trips between destination zones is reflected in the price of the trip itself since it is the composite or weighted average trip with which we are concerned. Consequently, the benefit computation is less uncertain than was that by the previous version of the method. It can still be accomplished using only the interzonal volumes and separations from each alternative network, but it will still contain

whatever uncertainty is introduced by the trip generation, distribution, and assignment models employed.

The major disadvantage of this version of the method is that it is not possible to identify the amount of difference in benefit accruing from travel between each zone pair. The change in benefit is computed on the basis of zone of origin, not zone pair. It can be shown, however, that if only a redistribution of trips results, that is, no trips are generated or deleted, the quantity of benefit difference for trips from a given origin zone is the same when computed by either of the two simplified versions of the method. Thus, for such a situation, the use of an average price for all trips from a given origin eliminates the problem due to trip-substitutability merely by changing the concept of the commodity being demanded. It should be noted that the change in benefit computed by the two methods does differ whenever the total number of trips is not the same from a given origin zone before and after the change in the network.

USE OF THE METHOD IN AN EXAMPLE PROBLEM

Of the three versions of the method presented, one provides the best combination of (a) computability using data output from the assignment process and (b) the ability to determine with reasonable accuracy just who benefits and who loses because of a given network alteration. That version is the one that views demand for travel on the basis



O Node that is also a Centroid of a Network-Loading Zone

• Node or Intersection

Figure 13. An example problem.

TABLE 1

USER BENEFIT BY ZONE OF ORIGIN

Zone	User Benefit in Vehicle-Minutes	Number of Vehicle Trips	Average Benefit per Trip in Minutes
1	+2654	5307	+0.5
2	-2970	7425	-0.4
3	+1238	4127	+0.3
4	+3508	7015	+0.5
5	+4637	5152	+0.9
6	+6124	7655	+0.8
7	+ 300	3003	+0.1
8	+ 189	1887	+0.1
9	+2344	3348	+0.7
10	+5500	9166	+0.6
11	-3406	8516	-0.4
12	+3913	9782	+0.4
13	+4914	6142	+0.8
14	+2809	7022	+0.4
15	0	7984	0
16	- 395	3954	-0.1
17	+ 652	6516	+0.1
Total	+32,011*	104,001	+0.3

*+32,011 vehicle-minutes per hour of morning peak period = 534 vehicle-hours per hour of morning peak period, or +0.3 minutes per vehicle-trip.

of origin zone rather than zone pair. Its use will be illustrated in an example case. First, however, a brief note is in order on the relationship of the method to present means of travel estimation.

Relationship to Trip Generation, Trip Distribution, and Traffic Assignment

With reference to Figure 10 and the first four cases presented there, the different number of interzonal trips demanded on network 2 compared with network 1 is assumed to be due to (a) the changed distribution of trips caused by differences in interzonal separations on network 2 compared with network 1, and (b) changes in trip generation when trip generation is dependent upon interzonal separation as well as on other parameters more of a socio-economic nature.

The different interzonal prices are the different interzonal separations over the alternative loaded networks. The different prices are due to:

1. For the first four cases of Figure 9, the change in demand, as outlined in the preceding paragraph, resulting in a changed level and distribution of the overall network load;
2. For all six cases of Figure 9, the change in minimum paths between zones due to the network differences.

For absolute consistency, the interzonal separations used to determine trip generation and/or distribution should be the same as those resulting from the loaded networks, the p_1 and p_2 of Figure 10. Since the trip generation and distribution phases normally occur before any traffic assignment (from which the separation measures result), some means of iteration of these several phases may have to be accomplished to assure that the interzonal separation measures finally used in each of the phases are in reasonable agreement.

An Example Problem

The example network is shown in Figure 13. The problem is to estimate the net benefit accruing from the addition of a new 8-lane divided highway to the network, link 20-26. In the problem, the measure of interzonal separation is merely travel time, but it could be out-of-pocket expense plus value of travel time or some similar more comprehensive measure.

The results of the application of the method to the evaluation (for only the morning peak period) of the addition of link 20-26 (and 26-20) to the network are shown in Table 1. The user benefit accruing to trips originating in each of the several zones is shown for the period concerned, the typical morning peak hour. Although the net user benefit is positive (534 vehicle-hours gain per morning peak hour), trips from all origin zones did not benefit. Thus the incidence of the benefits and losses by origin zone is revealed by the method. This attribute of the method is especially helpful when it is desired to improve travel from some particular geographical area or to ascertain the geographical distribution of the user benefits.

The benefits must be summed over all hours of the period for which the assigned traffic is typical. For the case shown in the example problem, the resulting 534 vehicle-hours/hour of benefit must be multiplied by the length of the morning peak period

in hours in order to get the total benefit accruing during that period. The same sort of calculations would be required for peak and off-peak or other periods in which the network load varied significantly during the average day. Then, the daily benefit thus obtained could be summed for the year or other length period. Furthermore, the growth in demand over time should be accounted for (12).

Proper discounting and summing of the benefits over the expected life of the proposed facility (link 20-26) will give the total user benefit to be compared with the estimated cost of the facility. Such a comparison would be on a present value basis. Benefit-cost ratio techniques could also be used.

LOGIC FOR A COMPUTER ROUTINE TO PERFORM THE METHOD OF EVALUATION

The proposed subroutine would take the output of a traffic assignment program and would then compute the incremental net user benefit of one alternative network as compared with another.

If data on the cost differences between alternative networks is available, the values of comparison criteria such as benefit-cost ratio or present worth could also be computed with the routine.

Any number of pair-wise comparisons can be made on the same run, provided specifications are correctly made and the required data and computer time are available. The following outline provides a more detailed explanation:

A. Input required

1. Specifications for run
   a. Number of networks to be compared
   b. Names of networks
   c. Designation (O&D) of interzonal transfers to be analyzed for each or all network pairs
   d. Desired criteria of evaluation (if any)
   e. Input data mode (cards, disk, etc.)
2. Input data
   a. For each alternative network
      (i) For each interzonal transfer, the volume and price at completion of assignment
      (ii) Costs (maintenance and construction) associated with each alternative network
      (iii) Interest rate(s) to be used in comparison criteria computation

B. Computation required

1. Pick first pair of alternative networks (alternative networks should be in order of increasing cost)
2. For network pair
   a. For each origin zone
      (i) Compute average price, $p_i^a = \sum_j p_{ij} q_{ij} / \sum_j q_{ij}$
      (ii) Compute net benefit [say, NETBEN (I) = $\frac{1}{2}({}_1q(I) + {}_2q(I))\,({}_1p^a(I) - {}_2p^a(I))$]
      (iii) Increment net benefit for this pair [say, BENSUM = NETBEN (I-1) + NETBEN (I)]
   b. Compute values of comparison criteria
3. Repeat 2 for each successive pair of alternative networks

C. Output: For each pair of network alternatives
1. The names of the network
2. The incremental net user benefit
3. The values of the comparison criteria

A flow chart of the subroutine as outlined appears in Figure 14.

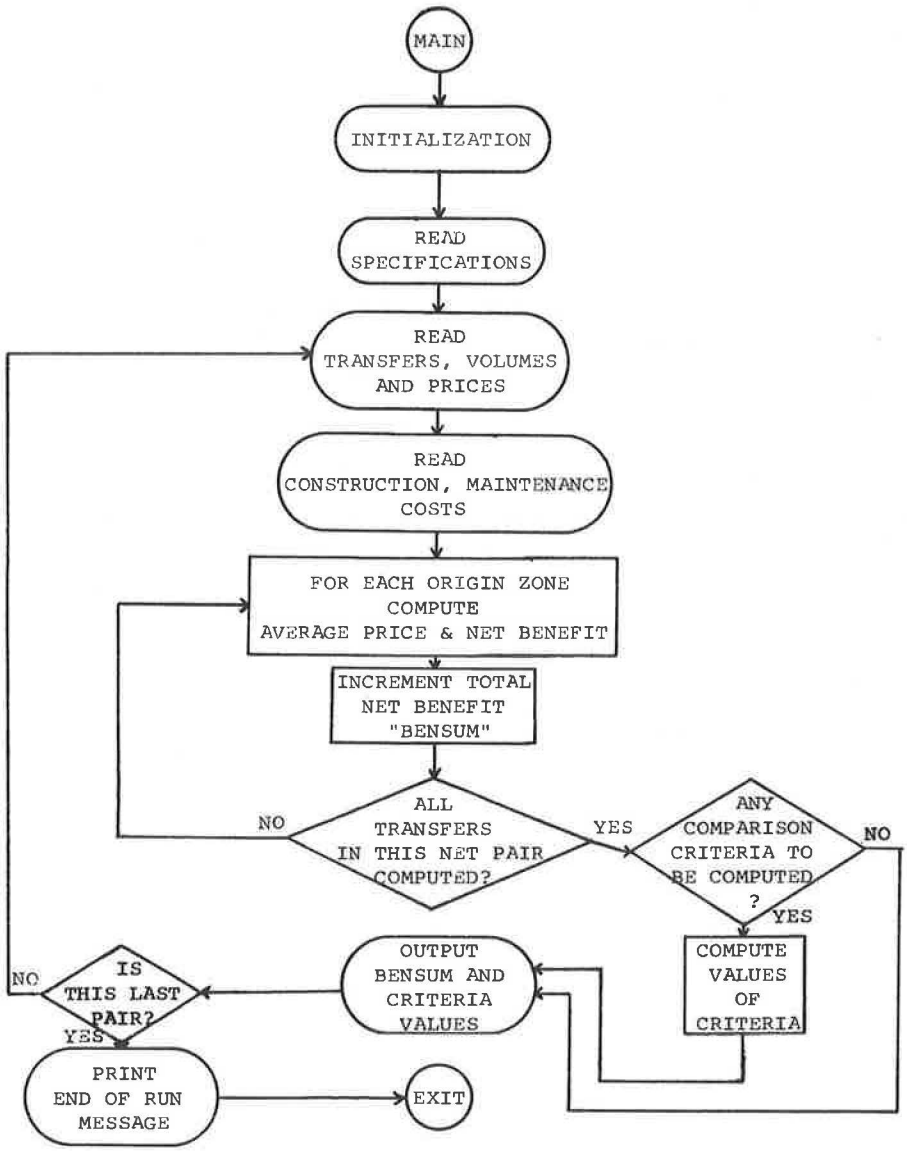


Figure 14. Example flow chart—computation of user benefit by origin zone.

CONCLUSION

The method of evaluation described in this paper makes it possible to compare networks even though the interzonal demand for travel over the two networks may differ. Of course, the differences in demand must be due to the different networks. Thus the effect of alternative networks on travel demand can be accounted for. Constant or fixed travel demand need not be assumed.

The method is based on a consistent economic rationale. It uses consumer surplus as a measure of benefit. The measure of net value produced by the method is only as comprehensive as the data on which the values of interzonal separation are based. There is, therefore, a need for more comprehensive measures of interzonal separation. It is desirable that those items of travel cost perceived by travelers and assessed by them in making travel decisions should be identified and included in some manner.

Although only two networks may be compared at a time, two of the versions of the method require estimation of only a partial segment of the demand curve for travel from each zone. Further investigation is needed to determine if the idealized version may be practically used with the multi-dimensional interzonal travel demand functions being developed by others.

Finally, the version advocated for current use requires only the interzonal volumes and the interzonal separations for each network being evaluated. It is not constrained, therefore, to any particular technique of traffic assignment, or for that matter, even to traffic assignment if reliable volume and separation data are available from some other source.

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REFERENCES

1. Harvey, T. N. Logic of a Subroutine for the Approximation of Incremental User Benefits on Highway Networks Using the Output of a Traffic Assignment Algorithm. Memorandum ITP 4, MIT Department of Civil Engineering, March 1, 1966.
2. Pollard, W. S., Jr. Long Range Urban Traffic Planning. In Traffic Engineering Handbook. Institute of Traffic Engineers, Washington, 1965, p. 703-723.
3. Haikalis, G., and Joseph, H. Economic Evaluation of Traffic Networks. HRB Bull. 306, p. 39-63, 1961.
4. Marshall, Alfred. Principles of Economics, Ninth (Variorum) Edition, Macmillan Co., 1961 (First Edition, 1891).
5. Samuelson, Paul A. Foundations of Economic Analysis. Atheneum, 1965, p. 195-202.
6. Mohring, Herbert D., and Harwitz, Mitchell. Highway Benefits—An Analytical Framework. Northwestern University Press, 1962, p. 23-26, 52-56.
7. Wohl, Martin. Demand, Cost, Price, and Capacity Relationships Applied to Travel Forecasting. Highway Research Record 38, p. 40-54, 1963. [See for discussion of the difference between marginal and average costs in a travel context.]
8. Soltman, Theodore J. Effects of Alternate Loading Sequences on Results From Chicago Trip Distribution and Assignment Model. Highway Research Record 114, p. 122-140, 1966.
9. Domencich, T. A., Kraft, G., and Valette, Jean-Paul. Estimation of Urban Passenger Behavior: An Economic Demand Model. Presented at the 47th Annual Meeting and included in this Record.
10. Quandt, R. E., and Baumol, W. J. The Demand for Abstract Transport Modes—Theory and Measurement. Jour. Regional Science, Vol. 6, No. 2, Winter 1966.
11. Samuelson, Paul A. Economics, Fifth Edition. McGraw-Hill, 1961, p. 436.
12. Wohl, Martin, and Martin, Brian V. Evaluation of Mutually Exclusive Design Projects. HRB Spec. Rept. 92, 1967, p. 50-51.