A Model for Highway Needs Evaluation

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The highway needs evaluation model is designed to provide the policy determination of the suitable level of highway investment in a large, primarily urbanized region and the allocation of this investment to subareas based on a common set of social and economic values. The influence of variations in expressway supply on the volume and distribution of travel and certain measures of travel cost, specified through regression analyses, is used to evaluate the overall effect of increasing the level of expressway supply. It was found that increases in expressway supply lead to increases in total travel volume and reductions in average travel cost per mile. This benefit to the highway user is balanced against the costs of increased supply in order to select the level of capital investments that provide maximum satisfaction of the established regional objectives. Sensitivity analysis is used to consider the effect, in terms of the investment supply level, of changes in the values placed on specific objectives included in the model. Those values to which the results are most sensitive are the value of travel time and the opportunity cost of capital. A brief discussion of suitable directions for future research and development is included.

•ONE OF THE KEY FUNCTIONS of the regional planning process is the determination of the need for capital investment in public systems. The selection of an appropriate level of investment in highway facilities is particularly significant because of the important effect the quality of the highway transportation system has on the development of the region and in view of the large portion of public capital that is allocated to highway construction.

This paper describes a model for determining a suitable level of highway investment in a large, primarily urbanized region and the allocation of this investment to subareas within the region based on a common set of social and economic considerations. The model offers the following advantages as compared to existing methods:

1. It requires a minimal amount of travel information.
2. The objective function may be modified to reflect the values of the region under study.
3. The importance of different objectives on the final proposal may be tested.
4. The objective function provides a basis for making trade-offs between the allocation of resources to high-density areas where costs and benefits are high and low-density areas where costs and benefits are low.
5. A general level of requirements, which will serve as a framework for development of more specific proposals, can be established early in the planning process.

The model is described in detail in the following sections of this paper.

HIGHWAY PLANNING OBJECTIVES

It has been reasoned that the logical objective of a transportation system is to assist society to achieve its basic needs and objectives (1). A suitable analytic approach is to

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consider highway planning decisions in a framework of providing high-quality travel service with an emphasis on functional efficiency and avoidance of negative social impacts.

The first stage in the process of developing an operational objective function is to list the relevant objectives:

1. To provide high-quality travel service (TRAV BEN);
2. To maintain a high level of functional efficiency, that is, (a) reduce travel time (TT), (b) reduce the number of accidents (ACC), (c) reduce vehicle operating costs (VEHOP), (d) reduce capital investment in highways (CCOST), and (e) reduce highway maintenance and operating costs (MCOST); and
3. To avoid or reduce negative social impacts such as (a) the disruption to communities and individual households caused by new highway construction (DISRUPT), (b) traffic penetration of local neighborhoods (TPLN), and (c) air pollution and traffic noise (POLL).

There are conflicts between some of these objectives. One method of resolving these conflicts is to assign weights to each objective and to define the overall highway planning objective as maximizing the weighted sum of these individual objectives. There are certain problems involved with any attempt to apply a universal value to some of the stated objectives. Nonetheless, such judgments must be and are being made daily. The use of a common set of values is justified in order to compare the relative needs of differing areas; the use of local values might be required in more specific studies.

In general form, the objective function can be expressed as

$$\text{Maximize} \left(\text{Travel Benefit} - \sum_{i=1}^{N} w_i C_i \right) \tag{1}$$

where C_i is the ith cost of travel measured on an appropriate scale such as hours, dollars, or occurrences; and w_i is the weight assigned to the ith cost. This objective function is shown in Figure 1, where the objective is to select the level of highway supply that will maximize net travel benefit.

For the sake of simplicity and ease of interpretation, equivalent daily dollar values will be used as weights for the individual objectives. The effect of the use of different weights will be considered in the section on sensitivity analysis.

Travel time savings are valued at $6.00 per commercial vehicle-hour based on driver salaries, fringe benefits, and vehicle depreciation and at $2.50 per passenger vehicle-hour based on per capita income in the region. The value of commercial vehicle time

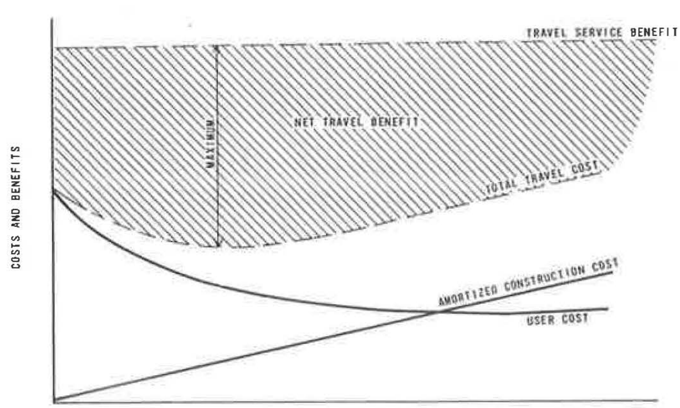

Figure 1. Highway planning objective function.

is obtained by adjusting the value of $5.16 for the Middle Atlantic Region in 1965 (2) by 3.5 percent per year up to 1969 to reflect increased costs. Average hourly income of wage earners in 1969 is estimated at $4.30. Distributing this income over the total population indicates a weighted average value of $1.80. Assuming that the average automobile occupancy is 1.4 persons, the value of passenger vehicle time is estimated at $2.50 per hour. Travel time savings are considered to be additive for valuation purposes; that is, all units of time savings will be valued at the same rate independent of their absolute size (2).

Average accident costs, $1,470 per reported accident on expressways and $925 per reported accident on arterials and local streets, were obtained by adjusting average per-involvement costs estimated for the Washington, D. C., area (3). An additional cost of $325 is assigned to reported accidents on arterials and local streets to represent the frequent occurrence of low-cost unreported accidents. Vehicle operating and maintenance costs are estimated from mileage driven, average speeds, and free speed, using relationships developed by Winfrey (4) and Schneider (5).

Previous studies have shown the relationship between construction costs (including right-of-way) and the density of development in the surrounding area (6). For this analysis the average cost of expressway construction is estimated as a function of population density and interchange spacing. The construction cost (Fig. 2) varies from $2 million per route mile in a rural area with interchanges spaced about 15 miles apart to $45 million per route mile with a 1-mile spacing between interchanges located in the center of the region. The capital recovery factor of 0.1446 is based on an opportunity cost of capital of 10 percent per year, a project life of 25 years, and the assumption that annual benefits vary from 50 percent of the target year value in the first year to 150 percent in the 25th year. On a daily basis this factor becomes 0.000396.

Highway maintenance and operating costs are estimated at $33,000 per mile of expressway per year, or approximately $90 per mile per day. This cost is based on highway maintenance and traffic services, law enforcement and safety, administration, and miscellaneous services for state-administered highways in New York, New Jersey, and Connecticut from 1963 to 1967, as reported in "Highway Statistics" and adjusted to allow for cost increases in 1969.

The social objectives are more difficult to value quantitatively. However, their significance is such that reasonable effort should be directed toward the development of methods for measuring and evaluating the effect of changes in the highway system on these objectives. To the extent that this is not accomplished, these objectives must be considered subjectively in the preparation of final recommendations.

Of the three items of social impact listed, only one—disruption caused by new construction—is amenable to quantitative estimation for the purposes of this study. We will assume that this element can be partially measured from the unreimbursed costs of community relocation of all types. A recent study in Baltimore indicated that unreimbursed monetary costs average about $3,500 for each relocated family (7). For simplicity, the unreimbursed relocation expenses for other private activities (stores, doctors' offices, etc.) and public activities (parks, schools, etc.) will be included by doubling the costs of household relocations (a very rough estimate) for an overall estimated equivalent cost of $7,000. Furthermore, there are additional nonmonetary costs associated with relocations and community disruptions. It seems reasonable then to include some allowance for these costs (say, an additional $3,000 per household for a total of $10,000) based

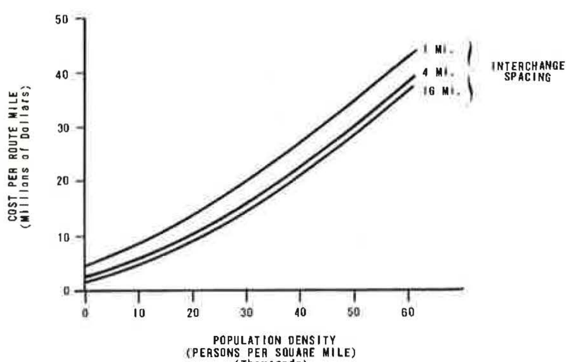

Figure 2. Construction and right-of-way cost per mile.

on the principle that individuals in the path of new highway construction should not suffer injuries as a result of programs designed for the benefit of the general public (8). Because of the one-time nature of relocation costs, they must be weighted by the same capital recovery factor applied to capital investment costs.

The number of household relocations is a function of the land area required for right-of-way and the population density of the area. Although efforts are made to avoid taking residential structures, in urbanized areas this can only be done at the sacrifice of other developed property.

The introduction of these weightings in the general objective function provides the following specific function for the Tri-State Region:

$$\text{Maximize} \begin{bmatrix} \text{Travel Benefit} - \$6.00\ TT_c - \$2.50\ TT_p - \$1{,}470\ ACC_E \\ -\ (\$925 + \$325)\ ACC_{AL} - VEHOP - 0.000396\ CCOST \\ -\ \$90\ RT\ MI_E - 0.000396 \cdot \$10{,}000\ HHREL \end{bmatrix} \quad (2)$$

where

TT_c = total travel time of commercial vehicles,
TT_p = total travel time of private vehicles,
ACC_E = the number of accidents expected on expressways,
ACC_{AL} = the number of accidents expected on arterials and local streets,
CCOST = the initial cost of road construction and right-of-way acquisition,
$RT\ MI_E$ = the route miles of expressway, and
HHREL = the number of expected household relocations.

This formulation provides a basis for estimation of the objective function except for the underlying benefit of highway travel, which is the most difficult to evaluate because of the lack of detailed knowledge of the benefits that accrue to individual highway users. Fortunately, this difficulty is not critical as long as the total benefit is assumed to be greater than the total user and nonuser costs. If the total volume of travel remains constant, the travel service benefit will remain constant and minimization of the weighted cost elements is equivalent to maximizing the objective function. If, however, the amount of travel increases (as will be discussed later), net benefits may be viewed in terms of consumer surplus.

In effect, this avoids counting any social benefit for the generation of additional travel based on the assumption that the benefits derived are just equal to or only marginally greater than the costs incurred when the trip becomes acceptable. However, further reductions in travel cost are applied to the generated travel as well as to the previously existing travel.

HIGHWAY TRAVEL DESCRIPTION

The satisfaction of individual objectives for any level of highway investment may be predicted through use of the highway travel description model developed for making such predictions for highway travel in the Tri-State Region. The model in Figure 3 is based on economic demand theory supported by observations of regular and repetitious travel behavior in the region and has the following general characteristics:

1. Vehicle-miles of travel can be predicted as a function of vehicle trip ends (origins or destinations) and the supply of expressways over any reasonable size area.
2. The ratio of vehicle-miles of travel to vehicle trip ends varies downward with increasing density but upward with increases in expressway supply.
3. The distribution of vehicle-miles of travel between different classes of facilities, although more sensitive to external factors, is also in the predictable range.
4. The proportion of travel on expressways increases as the supply of expressways is increased.
5. Travel on arterials and local streets decreases absolutely and proportionally as the supply of expressways is increased.

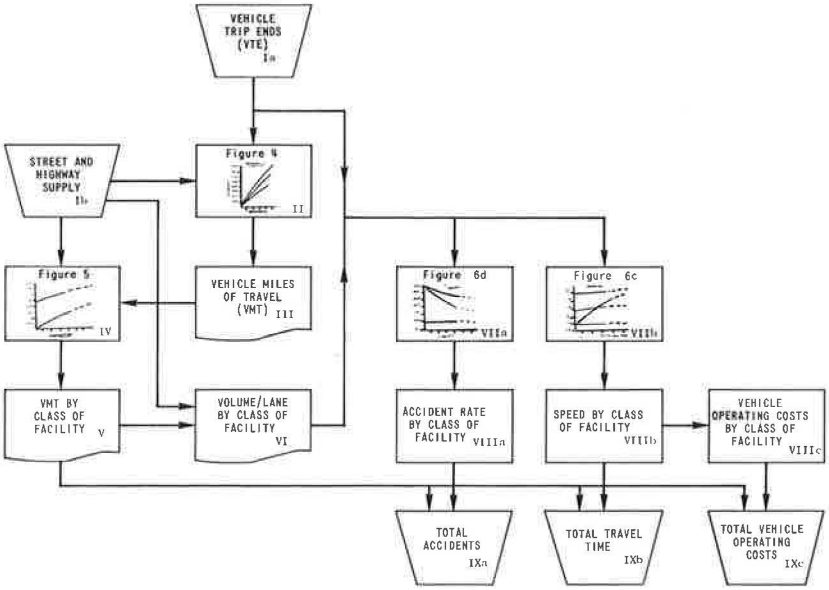

Figure 3. Highway travel description model.

6. Quantitative measures of performance, such as travel speed and accident rates, can be estimated from the loading on each facility class.

7. The descriptive ability is aimed at those characteristics that measure the degree of achievement of the objective function.

The first stage in the description of future highway travel requires the projection of vehicle trip ends. This projection is made by conventional techniques from previously established estimates of population, employment, household size, income, and automobile ownership.

The amount of travel that will actually take place on the streets and highways of the area, measured in terms of vehicle-miles of travel per square mile, can be estimated from this projection of vehicle trip ends per square mile by the following equation (Fig. 4):

$$VMT = 56.0\ VTE^{0.77} \tag{3}$$

where VMT is vehicle-miles of travel per square mile and VTE is vehicle trip ends per square mile. The root mean square error is 0.85.

Although Eq. 3 provides reasonable estimates of the total volume of motor vehicle travel, it is unsatisfactory in view of the lack of sensitivity (or elasticity) to variations in the supply of expressways. In general, an increase in expressway supply will cause a reduction in average travel cost and, if the demand for motor vehicle travel is not completely inelastic, will bring about an increase in the total volume of travel (9). The following structural equation was proposed to provide a degree of sensitivity to variations in expressway supply:

$$VMT = A \cdot VTE^{B}\ e^{(C \cdot PDS)} \tag{4}$$

where PDS is the proportion of area-wide net driving surface on expressways and A, B, C are unknown constants.

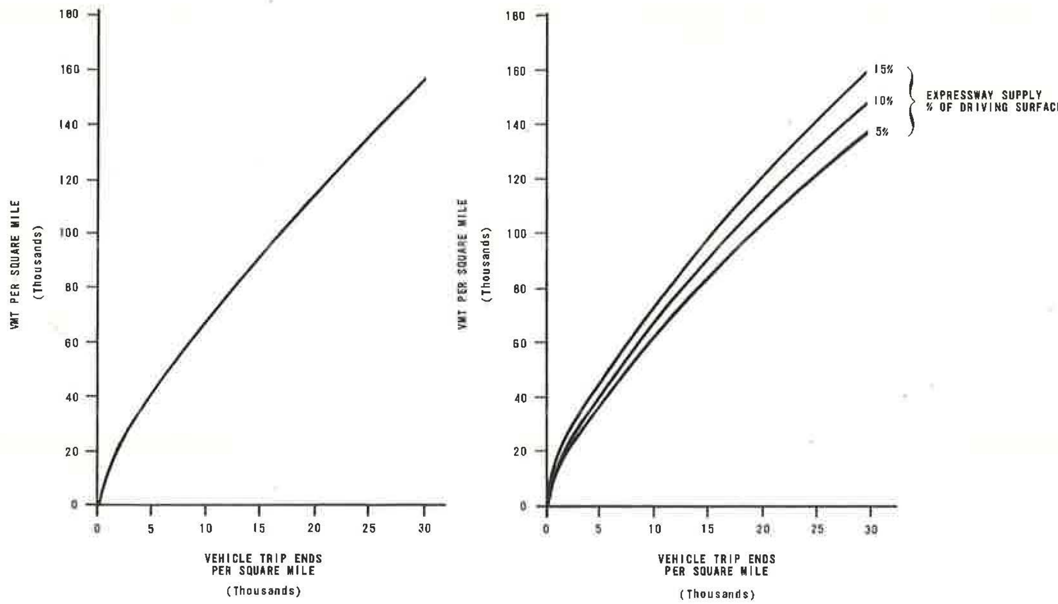

Figure 4. Projecting vehicle-miles of travel (a) as a function of vehicle trip ends and (b) as a function of vehicle trip ends and expressway supply.

Regression analysis was used to select values of A, B, and C that improved the ability to estimate vehicle-miles of travel and provided a reasonable level of response to changes in expressway supply.

The following equation was selected:

$$VMT = 64.3\ VTE^{0.74}\ e^{1.6\ PDS} \quad (5)$$

where VMT, VTE, and PDS are defined as before. The root mean square error is 0.91. The addition of the PDS term reduced the previously unexplained variation in VMT by 45 percent.

The ratio of vehicle-miles of travel to vehicle trip ends (VMT/VTE) decreases with increasing density and increases with increasing expressway supply as follows:

$$\frac{VMT}{VTE} = \frac{64.3\ e^{1.6\ PDS}}{VTE^{0.26}} \quad (6)$$

The decrease in this ratio with increasing density represents the discouragement to travel in high-density areas where travel costs are relatively high. The increase in the ratio with increases in expressway supply indicates the effect of providing a lower cost travel system as previously discussed. Both variations may be considered to include the effect of changes in the average length of trips with origin or destination in the area and as changes in the proportion and length of through trips in the area.

The distribution of travel on the different classes of roads is important in view of the differences in operating characteristics of the different classes of facilities. This distribution is determined by the relative supply of each type of facility measured by the relative driving surface and its ability to carry traffic (10).

The proportion of travel using expressways increases at a decreasing rate as the supply of expressways increases (Fig. 5). In the real range of operation, the redistribution effect is such that an increase in the supply of expressways leads to a decrease in the volume of travel on arterials and local streets. Consequently, an increase in the expressway supply will cause a decrease in average volume per lane on each class of facility.

The average speed of vehicles on each type of highway facility is determined by the design characteristics of the class of road and the delays caused by interference from other vehicles. The design characteristics determine the free speed. Delays resulting from friction between vehicles on the same roadway are related to the average volume per lane. Delays caused by entrances and exits and crossing movements of other vehicles are related to the density of automobile travel in the area, which can be measured by vehicle trip ends per square mile. The resulting speeds may be estimated by the following equations:

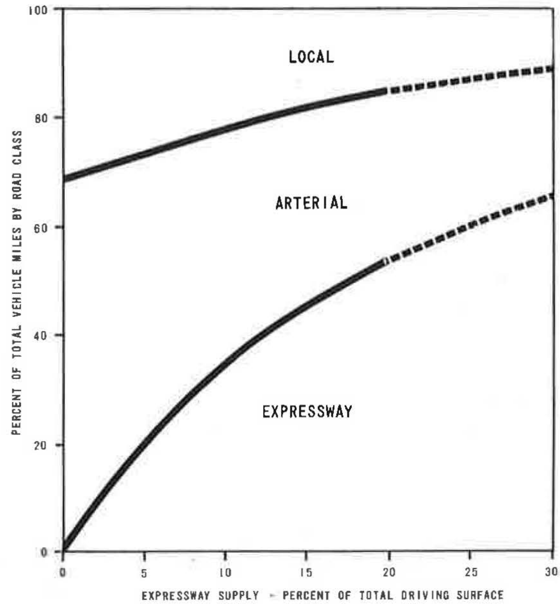

Figure 5. Effect of change in expressway supply on distribution of vehicle-miles of travel. Solid lines indicate the range of observed data (0 to 20 percent of road surface being expressways); dashed lines are extrapolated.

$$\text{SPD-EXP} = 55.3 - 0.73\ \text{VLE} - 5.19 \log \text{VTE} \qquad (7a)$$

$$\text{SPD-ART} = 32.7 - 1.21\ \text{VLA} - 8.64 \log \text{VTE} \qquad (7b)$$

$$\text{SPD-LOC} = 18.9 - 6.5 \log \text{VTE} \qquad (7c)$$

where

SPD-EXP = average speed on expressways,
SPD-ART = average speed on arterials,
SPD-LOC = average speed on local streets,
VLE = average volume per lane on expressways in thousands,
VLA = average volume per lane on arterials in thousands, and
VTE = average vehicle trip ends per square mile in thousands.

The root mean square error is 0.81 for Eq. 7a and 0.93 for Eq. 7b.

Accident rates on each class of road are also related to the friction between vehicles and can be estimated from measures of vehicle trip-end density by the following equations:

$$\text{ACC-EXP} = 160.0 + 12.0\ \text{VTE} \qquad (8a)$$

$$\text{ACC-AL} = 702.0 + 42.6\ \text{VTE} \qquad (8b)$$

where

ACC-EXP = accident rate per 100 million vehicle-miles of travel on expressways,
ACC-AL = accident rate per 100 million vehicle-miles of travel on arterials and local streets, and

VTE = average vehicle trip ends per square mile in thousands.

The root mean square error in Eq. 8b is 0.69.

The expected changes in vehicle-miles of travel, distribution of travel between road classes, accident rates, and average vehicle speeds resulting from increases in the supply of expressways are shown in Figure 6. The extent to which capital expenditures should be incurred to obtain the potential highway user benefits indicated will be explored in the next section.

Determination of Highway Supply

The procedure used to determine the supply level that maximizes the objective function is shown in Figure 7. The input consists of the projected trip ends, population density, supply of arterial and local streets for the target year, and the existing supply of expressways (I). A proposed supply of expressways, which in the first instance is equal to the presently existing supply, is assumed (II). The travel description model is used to simulate future highway travel, providing estimates of vehicle-miles of travel, total travel time for private and commercial vehicles, total accidents on expressways and other roads, and all vehicle operating costs (III). The objective function is then evaluated (IV).

If this is the first estimation of the objective function for the given area (that is, if the proposed expressway supply is equal to that presently existing), an increase in expressway supply will automatically be considered (dotted line from IV to VII); otherwise this value of the objective function is compared to previously obtained values of

Figure 6. Effect of change in expressway supply on travel parameters for sample area with 15,000 vehicle trip ends per square mile. Solid lines indicate the range of observed data (0 to 20 percent of road surface being expressways); dashed lines are extrapolated.

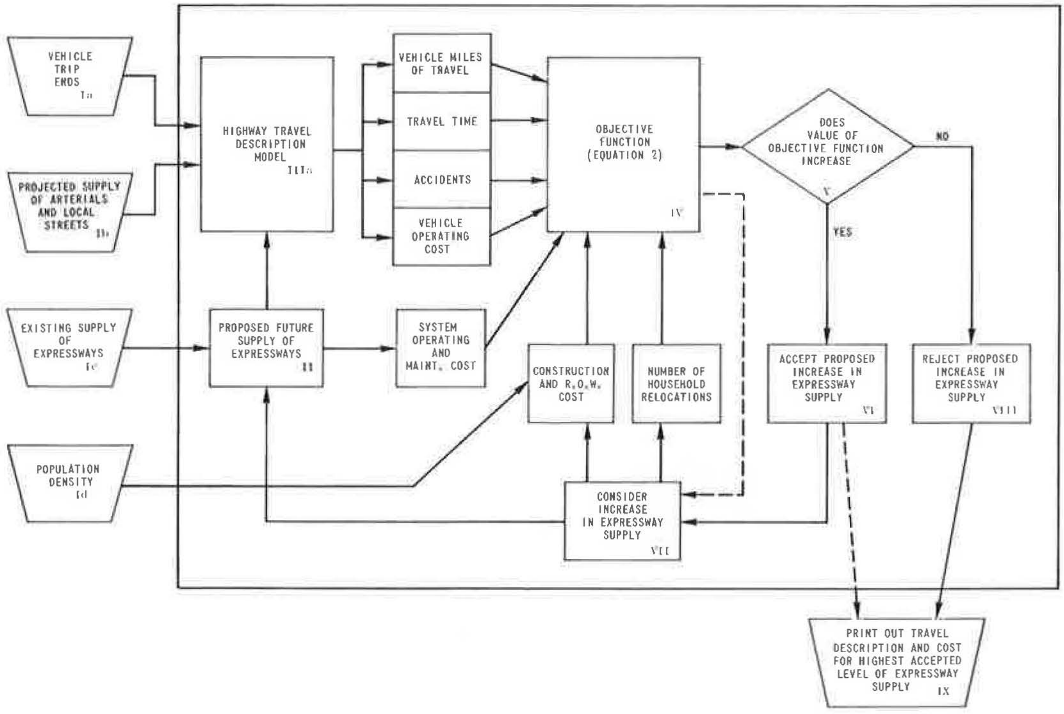

Figure 7. Model for highway needs determination.

the objective function at lower levels of expressway supply (V). If the value (i.e., the net benefit) has increased, the proposed future supply of expressways is accepted (VI) and a further increase in the expressway supply is proposed (VII). This process continues until the value of the objective function no longer increases with increases in the expressway supply, in which case the proposed increase in expressway supply is rejected (VIII). The resulting output (IX) is a description of travel cost and performance for the accepted level of expressway supply.

APPLICATION TO THE TRI-STATE REGION

The needs-determination program was applied to 83 analysis areas in the Tri-State Region. (The entire program required approximately 20 minutes operating time on the IBM 360/30. A FORTRAN program is available on request.) The output for each analysis area includes the recommended increase in expressway supply and the associated construction costs as well as estimates of future vehicle-miles of travel, distribution of travel between classes of facilities, average daily traffic volumes, average speed, and expected accidents.

The results of this analysis, summarized for the core area and three rings (Fig. 8), when compared to the previously published interim plan for the region indicated the need for a substantial increase in the proposed future expressway supply (Tables 1 and 2). Most of this increase in total needs is in the rapidly growing suburban portions of the region (Rings 1 and 2). This can be seen in the reduced average spacing between expressways, which represents the desired supply level, in the number of added route miles required, which makes allowance for existing facilities, and in the capital cost, which takes account of the variation in building costs in different portions of the region. The information obtained from this analysis is presently being used to guide the review and revision of the interim plan, which takes into consideration the network design factors and subjective evaluation of excluded social impacts.

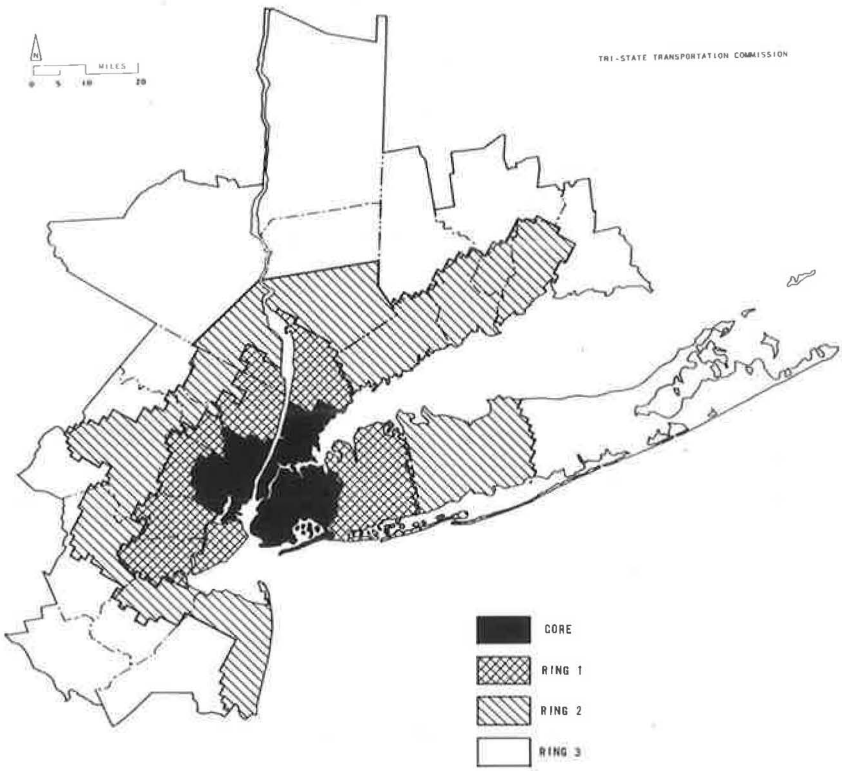

Figure 8. Data summary areas for highway needs in the Tri-State Region.

SENSITIVITY ANALYSIS

The weights assigned to the elements included in the objective function are subject to differences of opinion. Further, the assigned weights may vary over time and space. Sensitivity analysis can be used to indicate those elements for which the accuracy of the assigned weights is most important. The relative sensitivity of the results to variations in any of the objective weights has been estimated by considering the variation in average expressway spacing resulting from a variation of ± 10 percent in each of the objective weights (Table 3).

The cost of capital is the single most important factor in the list, with the value of time saved being much less sensitive but still quite significant. Study of both of these values should be emphasized in future research efforts. Variations of 10 percent in the remaining values cause only minor changes in the results obtained.

TABLE 1
HIGHWAY NEEDS EVALUATION PROGRAM

Area	Expressway Spacing		Added Expressways	
	1963	Proposed	Route Miles	Cost in Millions of Dollars
Core	3.1	1.9	190	2,200
Ring 1	7.4	2.4	550	3,650
Ring 2	15.7	4.1	820	3,770
Ring 3	32.8	11.2	520	1,740
Region	14.6	5.1	2,080	11,360

TABLE 2
HIGHWAY NEEDS INTERIM PLAN

Area	Expressway Spacing	Added Expressways	
		Route Miles	Cost in Millions of Dollars
Core	2.1	130	2,080
Ring 1	3.7	270	1,600
Ring 2	7.0	350	1,380
Ring 3	11.1	530	1,610
Region	6.8	1,280	6,670

TABLE 3

SENSITIVITY ANALYSIS FOR INFLUENCE OF OBJECTIVE FACTORS

Effect of 10 Percent Variation In	On Proposed Average Spacing Between Expressways[a] (percent)
Cost of capital	+11
Value of time saved	-7
Household relocation cost	+0.5
Accident costs	-0.3
Highway maintenance and operations	+0.2

[a]Average of change due to increase or decrease in factor weight. Sign indicates that change in result is in same direction (+) or opposite direction (-) as change in factor weight.

TABLE 4

SENSITIVITY ANALYSIS FOR SPEED ESTIMATES

Effect of 10 Percent Variation in Speed Estimated On	On Proposed Average Spacing Between Expressways[a] (percent)
Expressways	-6
Arterials	+9
Local streets	+6

[a]Average of change due to increase or decrease in speed estimate. Sign indicates that change in result is in same direction (+) or opposite direction (-) as change in speed estimate.

However, it is significant to note that the effect of completely ignoring community disruption as represented by the number of household relocations, which has actually been done in most studies, would be to overestimate the proposed expressway supply by more than 20 percent. This highlights the importance of considering such elements even if the exact weighting has not yet been established.

A similar approach was used to determine the relative significance of possible errors of some of the parameters used in the travel description model. Variations in the estimates of average vehicle speed, for all facility classes, turned out to be most critical (Table 4). This indicates the importance of improving our ability to predict future travel speeds.

FUTURE DEVELOPMENT OBJECTIVES

The work already completed in developing the method of needs evaluation described in this paper also indicates the need for additional work to broaden the potential application and improve the accuracy of needs estimates. Five specific areas of development are suggested:

1. Refinement of travel projections to include the feedback relationship between improved transportation facilities, land use, and future travel demands and the effect on highway travel of variations in the quality of transit service;
2. Refinement of the objective function based on improved valuations of the relative importance of individual objectives and consideration of the form of the equation to include the use of nonlinear relationships;
3. Exploration of the potential for, and importance of, incorporating additional social objectives in the objective function such as elimination of air pollution, reduction of traffic on local streets, and reduction of vehicle noise;
4. Refinement of technological relationships such as the equations used to estimate average travel speed and accident rates on different classes of facilities; and
5. Expansion of the model to include analysis of the supply of arterial as well as expressway facilities.

SUMMARY AND CONCLUSIONS

The needs estimation model described in this paper provides a useful method for evaluating highway needs in large metropolitan areas. The use of a consistent objective function provides a method for comparing the relative needs of disparate areas within a common region. The travel description model used provides reasonable estimates of future travel conditions sensitive to variations in the primary decision parameters. The approach described offers a simple method for obtaining approximate estimates of regional highway needs early in the transportation planning process at moderate cost in data collection and analysis. Further work will be directed toward refining the relationships used in order to obtain more reliable needs estimates in the future and toward expanding the scope of the model.

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