Urban Studies, Vol. 27, No. 1, 1990 119–138

Multicriteria Evaluation Approaches to Urban Transportation Projects

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[Paper first received, September 1987; in final form, April 1989]

Summary. The major objective of this paper is to examine the applicability of multicriteria evaluation methods to automobile restraint types of transportation projects. The examination was performed through applying the three multicriteria evaluation methods—concordance analysis, the goals-achievement matrix and the compromise solution—to automobile restraint policies in the context of Seoul, Korea. The results of the research show that the methods employed have, despite certain drawbacks, considerable potential for assisting the decision-maker and others concerned with the transportation decision-making process. Their major advantage over traditional transportation evaluation methods is that they allow the consideration of a wider range of costs and benefits. The empirical analysis also illustrates the usefulness of including qualitative criteria into the evaluation framework without transforming them to a monetary dimension.

I. Introduction

Transportation projects usually result in multiple and sometimes unidentified socio-economic and environmental consequences. Recognising the need to account for social, economic and environmental factors, transportation planners and analysts have devoted considerable effort to improving evaluation methodologies. Although some progress has been made in the development and refinement of evaluation methods, a common feature of much transportation analysis is that evaluation is based often on a single criterion, economic efficiency.

Traditionally, most transportation evaluation has centered around criteria such as travel time saving and cost minimisation. Other types of criteria have been largely overlooked as important decision parameters. Three reasons help explain the trend. First, there is a lack of a conceptual or theoretical evaluation framework which is suitable for transportation systems and which is multicriteria in scope. Secondly, criteria other than travel time or investment cost are considered to be of less importance, both to transportation analysts and decision-makers. Lastly, it has been difficult to obtain suitable data on more than a restricted set of criteria.

Multicriteria evaluation methods are generally designed to accommodate social, economic and environmental factors. Although some of the criteria are not measurable in an 'absolute' sense, the very fact that multidimensional factors are entered into the evaluation process through quantitative and qualitative analysis reflects the attraction of these methods. The insight

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provided by multicriteria evaluation methods can also lead to better communications between the analysts and decision-makers, lending to the latter a more effective role in the decision-making process.

Bearing in mind the advantages of multicriteria evaluation techniques, in the research reported here, three such methods have been selected in order to assess their strengths and limitations. Assessment is based on policies aimed at automobile restraint policies in the South Korean city of Seoul. The three methods chosen for this research are concordance analysis, the goals-achievement matrix and the compromise solution. Each is capable of handling multicriteria problems. The strength of these methods lies in their ability to use many measures of costs and benefits usually excluded from conventional economic analysis.

In this context, the issues addressed in this research are as follows: (1) whether the data on the criteria and automobile restraint policies are sufficient for each of the three methods. This issue is assessed empirically, and serves as a basis for deciding whether the three methods can be successfully applied to assessing transportation management strategies such as automobile restraint policies; (2) the best automobile restraint policies in the context of Seoul; (3) the major advantages and disadvantages inherent in the three methods in terms of various criteria.

II. Three Multicriteria Evaluation Methods

1. Concordance Analysis (CA)

Concordance analysis was developed by Roy (1968) and subsequently modified by Nijkamp and Vos (1977). This method is used for selecting one alternative from a set of alternatives with respect to relevant criteria. Each criterion is assigned a weight which corresponds to its relative importance.

The concordance between any two alternatives i and j is a weighted measure of the number of criteria for which alternative i is preferred to alternative j (denoted ${}_iP_j$) or for which alternative i is equal to alternative j (denoted ${}_iE_j$) and is expressed as

$$C(i, j) = \sum_{k \in A(ij)} w(k) \left[\sum_k w(k) \right]^{-1}$$

where $w(k)$ is the weight on criterion $k (k = 1, \ldots, K)$ and

$$A(i, j) = [k \mid {}_iP_j \cup {}_iE_j]$$

i.e. the set of criteria for which i is preferred to j or equal to j. Concordance is expressed in terms of absolute values with respect to alternatives and criteria.

The next step is to examine the relative degree of discordance between the various alternative pairs. This measures the degree to which outcomes of alternative i are worse than those of j. The discordance index is defined as

$$D(i, j) = \frac{\max[V(j, k) - V(i, K)]}{Z}$$

where $V(j, k)$ is the evaluation of alternative j with regard to criterion k, and Z is the largest of the K criterion scales.

The next step is to eliminate less favourable alternatives by setting threshold values ($\bar{c}$, $\bar{d}$). Threshold values are elicited from the decision-maker. By defining a critical value, one may state that alternative i outranks j if $C(i, j) > \bar{c}$ and $D(i, j) < \bar{d}$ with respect to each criterion.

2. Goals-Achievement Matrix (GAM)

The GAM method of evaluation was advanced by Morris Hill (Hill, 1967, 1968) and has been used for evaluating public projects (Miller, 1980). The GAM allows for the disaggregated treatment of cost and benefit accounting by objectives, and by the incidence of goal achievement through the relevant population.

The method retains qualitative data in the accounts and explores simple alternative weightings for the objectives and their differential impacts. The method's contribution to realism can be briefly summarised as a recognition of the full subjectivity of any formal weighting process and of the concomitant need to find a balanced means of presenting disaggregated information. The decision-makers may be provided with both a variety of alternative summary figures and the full set of underlying disaggregated accounts.

Hill proposes a methodology in which a separate cost–benefit analysis would be constructed for each goal, each goal weighted, and then the degree of achievement of weighted goals compared for each alternative.

The first step in Hill's methodology is the determination of goals, defined as "an end to which a planned course of action is directed". Goals include increased accessibility, reduction of displacement, separated pedestrian and vehicular traffic, minimised air pollution, and minimised traffic congestion. Hill suggests a number of approaches to goal selection, among which are consultation with elected officials and community groups, public opinion sampling, and examination of previous allocations of public investment. Hill believes that in practice, the number of important goals will be relatively small.

Once goals are selected, the impact of transportation alternatives on the goals is examined. Up to this point, Hill's goals-achievement matrix methodology is similar to a standard environmental impact statement. Important issues are identified (goals) and the future impacts of each alternative are estimated.

But Hill is not content merely to report the consequences of alternative actions; his methodology must make these consequences comparable. Early in his presentation Hill states that benefits such as reduced driving time cannot be directly added to the costs of air pollution.

Hill's solution to this problem of comparability is to aggregate similar impacts within each goal category and then compare the results for different alternatives. For example, the air quality impacts of highway alignment A at different locations would be added together and compared to the total air quality impacts of highway alignment B. One could indicate the better alternative with a '+' and the loser with a '−'. A more rigorous approach, which Hill also describes, is to convert the aggregated air quality impacts to a numerical scale which is referred to as its degree of goal achievement.

Alternatives can now be compared with respect to specific goals. 'A' may be superior to 'B' with respect to the goals of air quality and residential displacement, but 'B' may be superior to 'A' with respect to travel time and accident rates. If alternative selection is to be made on a rational basis, the dissimilar categories must be compared.

3. *Compromise Solution (CS)*

The compromise solution was developed by Zeleny (1982). It can be considered as being a member of the family of multicriteria evaluation methods, and is an attempt to provide decision-makers with the basis for selecting the best alternatives. This method is used in a situation involving multicriteria and is designed for deriving compromise solutions between the analyst and the decision-maker. The CS is a value-oriented approach in that the decision-maker should provide the analyst with several value judgments with regard to preference weights and membership functions. (The choice of membership functions simply indicates the means of achieving compromise.)

Zeleny (1976) suggests that because of the conflicting nature and noncommensurability of multicriteria, a concept of compromise solution, rather than optimal solution, is probably more useful for an analysis. By arguing that reliable construction of a utility function or trade-off function is often too complex or unrealistic to be practical, he viewed the CS as an effort to

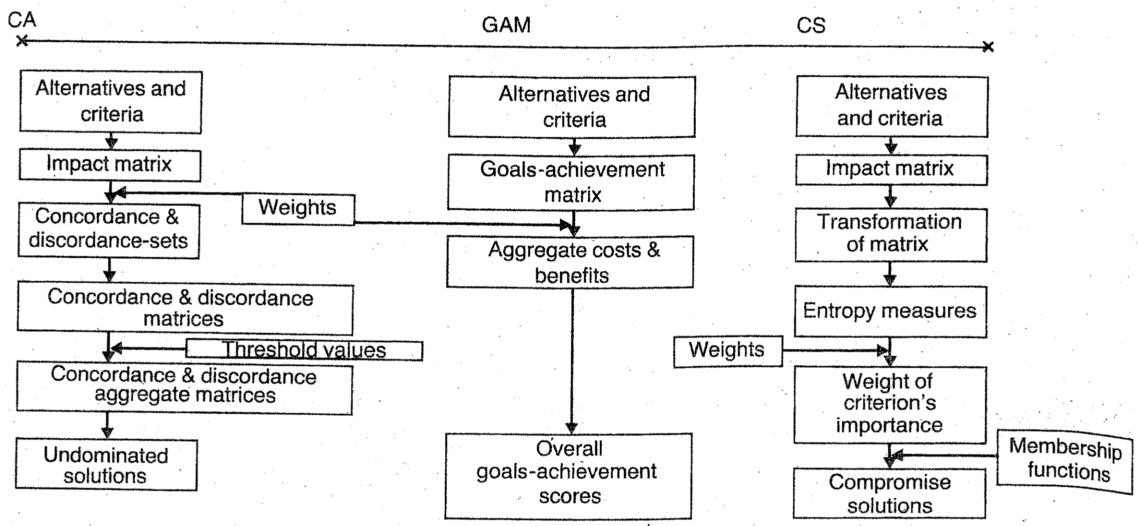

Figure 1. Major components of the three methods.

help the decision-makers to reduce the set of nondominated solutions by eliminating obviously bad solutions.

The underlying logic behind the CS is built upon the notion that among all achievable scores for any ith criterion there must be at least one extreme ideal value that is preferred to all others. The ideal point can be denoted by a_i^*. This can be stated as:

$$a_i^* = \text{Max}\, x_i^k \qquad i = 1, 2, \ldots, n$$

It is hard to reach the ideal point in the decision-making process. Therefore, an alternative solution should be sought which would be as close as possible to the ideal.

The next step is to transform all a_i^k into membership functions. The membership function, denoted by z_i^k, is designed to map the scores of ith criterion into the interval (0, 1) (Zadeh, 1974). The membership function can be interpreted as the degree of closeness to the ideal point p_i^k. The degree of closeness to a_i^*, the ideal point, has the following properties:

(1) If a_i^* is a maximum and a_i^* a minimum, then

$$z_i^k = \frac{a_i^k}{a_i^*} \qquad z_i^k = \frac{a_i^*}{a_i^k}$$

(2) If a_i^* is a feasible goal value, then

$$z_i^k = \left[\frac{1}{2}\left(\frac{a_i^k}{a_i^*} + \frac{a_i^*}{a_i^k}\right)\right]^{-1}$$

(3) If the most distant feasible score is to be labelled zero regardless of its actual closeness to a_i^* it can be expressed as:

$$a_{i*} = \text{Min}_k\, a_i^{k1} \qquad z_i^k = \frac{a_i^k - a_{i*}}{a_i^* - a_{i*}}$$

The above three functions of a_i^k mean that alternative a^j is preferred to alternative a^k when $z_i^k < z_i^j$.

Having discussed the underlying theoretical structure of the three methods, it seems appropriate to summarise these methods. As shown in Figure 1, the inputs or the initial information required by the three methods are the alternatives (transportation plans) and criteria (performance measures). These are the essential inputs for the analysis, and remain the same for all three methods. After the impacts are predicted on the basis of the chosen criteria and the alternatives, weights should be assigned to all criteria.

These weights represent the relative preferences of the decision-maker (or decision-making groups) for each criterion. The weights can provide a basis for deriving pairwise comparisons of competing alternatives in the CA, aggregate impacts in the GAM and the weight of criterion's importance in the CS. All that remains is to choose the best (undominated) alternatives by threshold values in the CA and by membership functions in the CS. The GAM does not need these types of values to arrive at the best alternatives as its underlying logic assumes that the decision-making groups' preferences are fully reflected in the aggregate impact matrix.

The foregoing discussion has been necessarily brief, but it indicates the basic stages of the three methods, namely:

(1) the prediction of the impacts and the generation of alternatives;
(2) the formulation of the weights decided by the decision-makers;
(3) the derivation of the best alternatives by threshold values in the CA and membership functions in the CS.

III. Implementation of Three Multicriteria Evaluation Methods

1. Transportation Problems in Seoul

The growth of traffic flow in the Seoul metropolitan area is causing increasingly serious problems of travel congestion and environmental degradation. The problems of congestion are inflicted on all travellers whether they are in cars, taxis, buses, or trucks, or are pedestrians. Likewise, these same problems affect the efficient and safe movement of goods. The resultant travel delays and accidents are a serious financial burden to the citizens and businesses of Seoul.

The growth of travel problems in Seoul has arisen from the rapid development of the city, in turn reflecting its economic growth. While the population in Korea as a whole has grown at a rate of 1.53 per cent per year between 1975 and 1984, Seoul's population has increased at a rate of almost 4 per cent per year over this same period.

Urban population growth is not the only factor affecting the growth of the traffic problem. The economic growth of the Seoul region is also critical, since it affects both vehicle ownership and travel consumption. For example, in 1984 Seoul, with slightly over 24 per cent of the national population, had over 41 per cent of the total vehicles registered in Korea. In the first three months of 1985 alone, vehicle ownership in Seoul has risen at an effective annual rate of 18.5 per cent.

Increased travel demands are being made on a transportation system that is already lower in capacity than those of many other major cities (Figure 2). Only 14.5 per cent of the land in Seoul is devoted to streets, compared with 20 to 35 per cent in many American and European cities, yet land use is much more dense in Seoul. Current deficiencies in the transport system are illustrated by the following facts:

- The number of fatal traffic accidents per vehicle in Seoul is seven times as high as that in US cities.
- Of the total traffic approaching the Central Business District (CBD) of Seoul, 53% has a destination other than the central area, burdening already congested streets.
- Bus system inefficiencies are illustrated by average vehicle loads of only 32–66 passengers per vehicle, despite the fact that at the same time many buses are carrying crush loads of 120–140 passengers during peak hours, and some streets have up to four lanes completely occupied by buses.
- The average volume/capacity ratio for major arterials in the CBD is 1.2 during morning peak hours.
- The rapidly growing vehicle fleet is outstripping roadway capacity.
- The existing major street pattern focuses far too much traffic on the CBD of Seoul.

Since travel demand, which is already inadequately served, threatens to far outstrip transport capabilities, some system of restraining automobile usage in the city center is widely acknowledged as necessary. Schemes available for restricting automobile traffic are numerous and may be applied to cities of different size and transport situation.

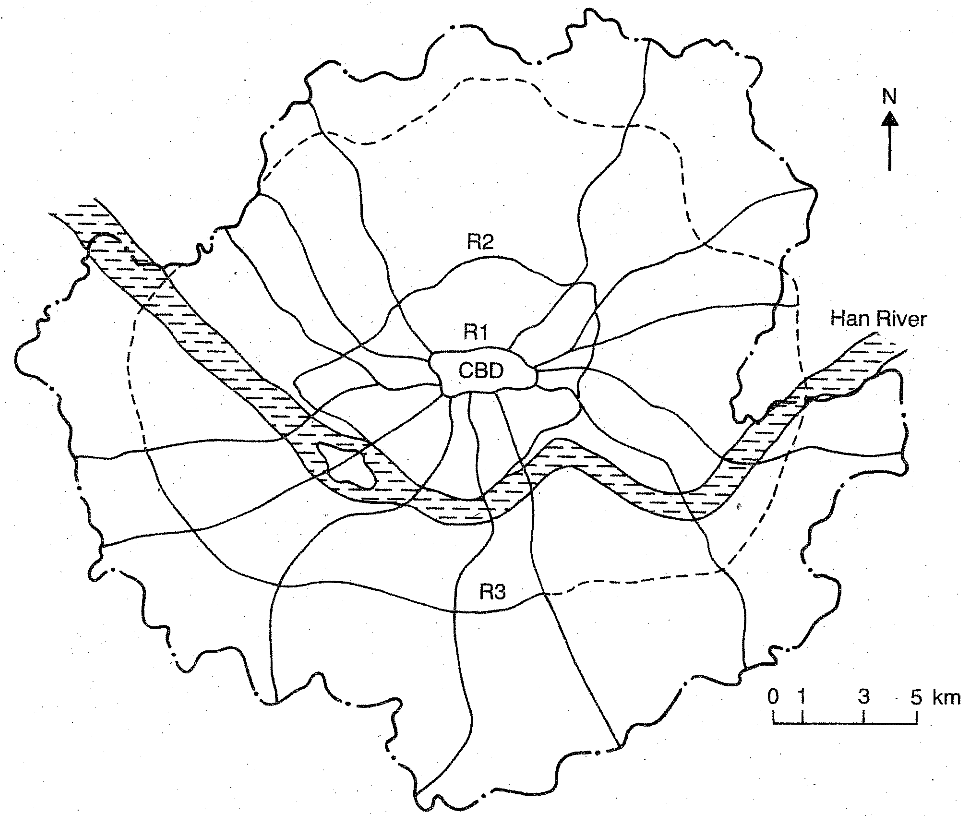

Figure 2. Major road network in Seoul metropolitan area. R1–R3, ring roads; (– – –) ring roads planned to be built; (—·—) metropolitan boundary.

2. Development of Automobile Restraint Policies and Multicriteria

Having described the transportation problems in Seoul, the next step is to determine the set of criteria and automobile restraint policies to be used for the multicriteria analysis.

In order to obtain the opinions of public officials engaged in transportation planning concerning auto restraint schemes, a survey of objectives and auto restraint alternatives in the context of the CBD was conducted within the Bureau of Urban Transportation, Urban Planning and Police (Traffic Control Center). A questionnaire was distributed among the staff in these bureaux (Table 1). Sixteen public officials responded to the survey.

The list of objectives and auto restraint alternatives was ranked in terms of their importance to the transportation situation in the CBD. The ranking was based on a scale between 0 and 10, where 10 indicates the most desirable objective or alternative.

Using unweighted average ranking, the seven top-ranked ARAs were selected:

a. Off-street parking fee increase
b. Extensive parking meter installation
c. Public transit priority signals around core ring
d. Core area licence scheme
e. Core area licence with transit improvement
f. Toll increase for tunnel gates
g. Toll charges at bridge entrances

An impact matrix, required for the three multicriteria analyses, can be calculated based on information which reflects all the relevant outcomes of each alternative (Table 2). The results of the impact matrix are presented in Table 3. The criteria are measured in such a way that a high value of an impact is preferred to a low value,

Table 1. Survey questionnaire

Objectives	Rank
1. Minimise capital cost	
2. Minimise current operating cost	
3. Maximise revenue	
4. Reduce travel time for auto and taxi	
5. Reduce travel time for public transit	
6. Reduce pollution	
7. Minimise traffic accident	
8. Minimise institutional obstacle	
9. Minimise enforcement problem	
Auto restraint alternatives (ARA)	**Rank**
a. On-street parking fee increase	
b. Extensive parking meter installation	
c. Public transit priority signals	
d. Core area license scheme (ALS)	
e. Core ALS with transit improvement	
f. Toll increase for tunnel gates	
g. Toll charges at bridge entrances	
h. Outer area license scheme	
i. Toll charge at bridges with parking lots	
j. Pedestrian streets	
k. Entrance ramp metering at bridges	
l. Outer ALS with transit improvement	
m. Outer ALS with transit improvement and fringe parking lots	

Table 2. Objectives and criteria

Objectives	Criteria
1. Minimise capital costs	Cost (monetary)
2. Minimise current operating costs	Cost (monetary)
3. Maximise revenues	Monetary value
4. Reduce travel time for auto and taxi	OVTT[a] saved for auto
	OVTT saved for taxi
	OVTT saved for bus
5. Reduce travel time for public transit	IVTT[b] saved for auto
	IVTT saved for taxi
	IVTT saved for bus
6. Reduce pollution	Pollution level measured on ordinal scale for auto, taxi and bus
7. Minimise institutional obstacles	Institutional preference index
8. Minimise enforcement problems	Enforceability index

[a] OVTT is out-of-vehicle travel time.
[b] IVTT is in-vehicle travel time.

Table 3. Impact matrix[a]

	1[b]	2	3	4	5	6	7
1. Capital cost	0	80	65	48	41.5	4	160
2. Operating cost	0	78	156	190.5	268.5	14.4	7.2
3. Revenue	0	285	0	76 013	76 013	4782	24 283
4. OVTT for auto	−1575	−630	0	−945	−945	−315	−315
5. OVTT for taxi	−630	−630	0	−1575	−945	−945	−630
6. OVTT for bus	0	0	315	315	−315	0	315
7. IVTT for auto	−630	−1260	630	−1890	−1575	−1260	−630
8. IVTT for taxi	0	−630	630	−1890	−1575	−630	−945
9. IVTT for bus	0	−315	−1260	−1260	−1260	−945	−945
10. Reduction	0.052	0.089	0.126	0.246	0.197	0.108	0.182
11. Institutional preference	0.190	0.173	0.137	0.108	0.093	0.221	0.077
12. Enforceability	0.196	0.165	0.133	0.127	0.067	0.215	0.097

[a] This table includes nine quantifiable and three non-quantifiable impacts with respect of each of the seven alternatives.
[b] Automobile restraint policies: 1, off-street parking fee increase; 2, parking meters in core area; 3, transit priority signals; 4, core area license scheme (ALS); 5, core ALS with bus improvement; 6, toll increase for tunnel gates; 7, toll charge at bridges.

Table 4. Concordance matrix, $\mathbf{C}(i, j)$

	1	2	3	4	5	6	7
1	—	0.594	0.671	0.575	0.393	0.311	0.797
2	0.326	—	0.615	0.519	0.519	0.259	0.542
3	0.249	0.305	—	0.539	0.539	0.249	0.522
4	0.425	0.481	0.461	—	0.762	0.425	0.745
5	0.628	0.481	0.461	0.238	—	0.607	0.663
6	0.689	0.741	0.751	0.575	0.393	—	0.744
7	0.385	0.458	0.478	0.255	0.410	0.256	—

except for criteria 1 and 2, in which the reverse is true. Capital costs, operating costs and revenues are given for seven alternatives through information provided by city government. The criteria relating to travel time come from a transportation equilibrium model which leads to the estimation of the change in travel time. The equilibrium model is constructed based on transportation supply, through network representation and demand, using origin--destination flows and a multinomial logit model for modal split. Criteria 10, 11 and 12 are based on the weighting method developed by Churchman and Ackoff.

As described earlier, the next step is to specify weights in order to use a multicriteria form of analysis. The need to specify such weights is considered one of the drawbacks of multicriteria analyses because of the difficulties and inherent arbitrariness in choosing them. A set of weights, denoted by row vector $\mathbf{w}$, was obtained from the 16 public officials. This set is presented as follows:

$$\mathbf{w}=\begin{bmatrix} \overset{1}{0.056} & \overset{2}{0.073} & \overset{3}{0.080} & \overset{4}{0.000} \\ \overset{5}{0.019} & \overset{6}{0.182} & \overset{7}{0.021} & \overset{8}{0.056} \\ \overset{9}{0.202} & \overset{10}{0.047} & \overset{11}{0.136} & \overset{12}{0.128} \end{bmatrix}$$

3. *Empirical Analysis*

Against the background of auto restraint policies and the multicriteria, this section is devoted to the empirical analysis. The three multicriteria evaluation methods require transformation of the impact matrix into dimensionless units. Each criterion should be divided by the maximum value of that criterion.

(1) *Concordance analysis*. Using the normalised impact matrix and a set of weights, concordance and discordance pairs can be calculated. These are calculated for each pair of alternatives. These pairs are used to derive a concordance matrix (Table 4) and discordance matrix (Table 5).

The next step to be undertaken is the elimination of less favourable alternatives. The threshold value for the concordance index of 0.200 and discordance index of 0.700 were used to reduce the number of alternatives. The reduction was done through 0–1 concordance and discordance dominance matrices, **G**, **H** and aggregation, **T**.

$$\mathbf{G}=\begin{bmatrix} - & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & - & 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & - & 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & - & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & - & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & - & 1 \\ 1 & 1 & 1 & 1 & 1 & 0 & 1 \end{bmatrix}$$

$$\mathbf{H}=\begin{bmatrix} - & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & - & 0 & 0 & 0 & 1 & 1 \\ 1 & 1 & - & 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & - & 0 & 0 & 1 \\ 0 & 0 & 1 & 1 & - & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 & - & 1 \\ 0 & 0 & 1 & 1 & 0 & 0 & - \end{bmatrix}$$

$$\mathbf{T}=\begin{bmatrix} - & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & - & 0 & 0 & 0 & 1 & 1 \\ 0 & 1 & - & 0 & 0 & 0 & 1 \\ 0 & 1 & 1 & - & 0 & 0 & 1 \\ 0 & 0 & 1 & 1 & - & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 & - & 1 \\ 0 & 0 & 1 & 1 & 0 & 0 & - \end{bmatrix}$$

Table 5. Discordance matrix, $\mathbf{D}(i, j)$

	1	2	3	4	5	6	7
1	—	0.336	1.00	1.00	1.00	0.752	0.752
2	0.500	—	0.748	0.800	1.00	0.688	0.627
3	0.575	0.507	—	1.00	1.00	0.688	0.627
4	0.712	0.500	0.250	—	1.00	0.938	0.685
5	1.00	0.712	0.425	0.421	—	1.00	0.973
6	0.055	0.000	0.248	0.913	0.913	—	0.338
7	1.00	0.875	0.589	0.696	1.00	0.982	—

Table 6. Goals-achievement matrix

	*a*1	*a*2	*a*3	*a*4	*a*5	*a*6	*a*7
*c*1	0.0	28.0	22.74	16.80	14.50	1.40	56.0
*c*2	0.0	21.24	42.41	51.76	73.0	3.94	1.97
*c*3	0.0	0.0	0.0	80	80	5.04	25.52
*c*4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
*c*5	7.6	7.6	0.0	19.0	11.4	11.4	7.6
*c*6	182.0	182.0	0.0	0.0	364.0	182.0	0.0
*c*7	7.0	14.01	−7.0	21.0	17.50	14.01	7.0
*c*8	0.0	18.65	−18.65	56.0	46.65	18.65	28.0
*c*9	0.0	50.50	202.0	202.0	202.0	151.5	151.5
*c*10	9.92	17.01	24.06	47.0	37.65	20.63	34.78
*c*11	116.96	106.49	84.32	66.50	57.26	136.0	47.33
*c*12	116.74	98.18	79.23	79.23	39.94	128.0	57.73
Benefits	440.22	494.44	363.96	570.73	856.4	667.23	359.46
Costs	0	49.24	65.15	68.56	87.50	5.34	57.97
Benefits−costs	440.22	445.2	298.81	502.7	768.9	661.89	301.49

The findings based on this analysis suggest that area licence schemes appear to be more favourable than other automobile restraint policies.

This outcome is generally consistent with the *a priori* expectation that the ALS is very effective in reducing OVTT and IVTT for the bus mode, both of which have been assigned high weights. The other reason for the final outcome seems to be that the ALS with bus improvement would not require any municipal expenditure associated with bus improvements. Bus improvement costs are to be borne by private companies. While the capital and maintenance costs required for instituting ALS schemes seem rather high, the remaining criteria are more than enough to offset these cost-related criteria. Despite the low weight scores on the institutional preference and enforceability, the two ALSs outranked the other alternatives on criteria relating to travel time, pollution and revenue, each of which is generally considered important.

(2) *Goals-achievement matrix.* As discussed in the theory section, the first step in the GAM is to determine the goals and estimate the impact matrix. The impact matrix and the set of weights already derived were directly applied in calculating overall scores.

The next step is to aggregate similar impacts within each goal category and then to compare the results for different alternatives. Table 6 was constructed by multiplying each value in a normalised impact matrix by the corresponding weight of the criteria. Benefits and costs were summed separately, and aggregate costs are subtracted from aggregate benefits.

The ALS with bus improvement receives the highest overall weighted scores (696.9), followed closely by the toll increase for tunnel gates. As far as the most desired ARA is concerned, both the CA and the GAM select the ALS with bus improvement. While the underlying structure of both methods differs substantially, the results obtained by the elimination of less favorable alternatives through a pairwise comparison in the CA turned out to be similar to those obtained by subtracting cost-related goals-achievement scores from benefit-related goals-achievement scores in the GAM. Thus it may be argued that the undominated solution in the concordance analysis is the same as the alternative that receives the highest score in the goal-achievement analysis.

(3) *Compromise solution (CS).* Within this method the objective is the identification of the ideal point for each criterion against the different policies. The set of alternatives is mapped through z_i^k values into a distance space. The next step is to derive a normalisation table. The individual components of each criterion are added up to 1 so that the set of automobile restraint policies is mapped onto unit interval (0, 1).

The next step is to derive an entropy value or a measure of 'contrast intensity'. The entropy measure is required for the derivation of the weights for the criteria. Since there are seven alternatives, e^{max} and k were obtained as follows:

$$e^{max} = \ln 7 = 1.946$$
$$k = ye^{max} = 0.5139$$

Using e^{max}, the entropy measure can be calculated. Then E, the sum of all $e(z_i)$, can be calculated. E was used to derive $\bar{g}_i$, a weight of each criterion's importance. The values of g stand for the relative contrast intensities measuring the intrinsic average information transmitted by each criterion. The final weights to be assigned were then calculated using and w_i and g_i.

The next step is to substitute the value of g_i into the distance membership functions, L^p matrices, so that the compromise solutions can be obtained for $p=1$, 2, max. When $p=1$ was used the ALS with bus improvement has the smallest value (0.162) representing the closest value to the ideal (Table 7). When $p=\max$ it is difficult to identify the closest value because alternatives 3, 4, and 5 show identical values to three decimal points. Thus calculation was performed up to six decimal points in order to derive a ranking. The results of the CS seem to imply that the method may not be effective in providing a ranking among the preferred alternatives.

When the value of $p=2$ is used, the fourth alternative, the Core Area License Scheme was the closest to the ideal point. The ALS alternatives have the property of being as close as possible to the ideal solution. The reason seems to be that the ALS alternatives received relatively higher weights from the decision-makers. For example, criteria such as OVTT and IVTT for bus trips seem far more effective under ALS schemes than under the other alternatives, because the public officials give high weights to these criteria.

In other words, while the city government incurs financial burdens in the ALS case, its returns, expressed in 'revenue', seem very high, perhaps inordinately so in the case of the ALS with bus improvement. In total, the ALS schemes retain their superior advantage for travel times by bus. Also, it would seem that the clear advantage of the ALS scheme is not too heavily eroded by low weights received for institutional preference and enforceability criteria. The outcome confirms that ALS alternatives are clearly superior to the other alternatives.

Table 7. Values for $g_i(z_i^* - z_i^k)$

	a1	a2	a3	a4	a5	a6	a7
c1	0	0.158 970	0.158 976	0.158 967	0.158 962	0.158 960	0.158 990
c2	0	0	0	0	0	0.207 000	0.207 000
c3	0.098	0.098 000	0.098 000	0	0	0.091 000	0.056 000
c4	0	0	0	0	0	0	0
c5	−0.036	−0.036 000	0.024 000	0	−0.016 000	−0.016 000	−0.036 000
c6	0.329	0.329 000	0	0	0	0.329 000	0
c7	−0.024	−0.006 000	0.048 000	0	−0.002 000	−0.006 000	−0.024 000
c8	0.024	−0.048 000	0.096 000	0	−0.005 000	−0.048 000	−0.024 000
c9	0.098	−0.294 000	0	0	0	−0.033 333	−0.033 000
c10	0.009	0.008 000	0.006 000	0	0.002 000	0.007 000	0.003 000
c11	0.002	0.003 000	0.005 000	0.006 000	0.007 000	0	0.008 000
c12	0.002	0.006 000	0.009 000	0.010 000	0.017 000	0	0.013 000
$p=1$	0.502	0.219 000	0.445 000	0.175 000	0.162 000	0.690 000	0.353 000
Max	0.329	0.329 000	0.158 976	0.158 967	0.158 962	0.329 000	0.207 000

Table 8. Assessment of the methods against the criteria

Criteria	Methods		
	CA	GAM	CS
(a) Computational Burden			
(1) Information requirement	−	+	−
(2) Computational efficiency	−	+	−
(3) Possibility of sensitivity analysis	++	−	++
(4) Inclusion of qualitative information	++	+++	++
(b) Degree of Interaction with the Decision-maker			
(1) Understandability of methods	−	++	−
(2) Encouragement of public participation	−	+++	−
(3) Interaction requirement	++	−	++
(c) Real-world Applicability			
(1) Applicability to auto restraint	++	+	++
(2) Applicability to large-scale transport project	−	++	−
(3) Incorporation of uncertainty	+	+	−
(4) Linkage to planning process	−	+	−
(5) Linkage to decision-making process	+	++	−

+++, very favourable; ++, favourable; +, moderately favourable; −, less favourable.

IV. Evaluation of the Three Multicriteria Methods (CA, GAM, CS)

Evaluating the three methods is itself a multicriteria problem. A number of criteria can be established in order to conduct the evaluation. The intent here is not to suggest which is the best method, for, as will become apparent, the methods examined have counterbalancing strengths and weaknesses. Although the needs, and thus criteria, for evaluating the methods are likely to vary for particular circumstances and decision-makers, several criteria must enter into the evaluation of methods in virtually all circumstances. The criteria to be considered are as follows:

(a) Computational burden
(b) Incorporation of transportation effects
(c) Degree of interaction with the decision-maker
(d) Ease of testing for sensitivity
(e) Real-world applicability

Table 8 summarises the basic assessment of each of the three methods against these criteria. The results are ranked according to whether each method scores favourably or unfavourably. Undoubtedly, the criteria are not all of equal importance. Each method has both advantages and disadvantages; no method is strongly favourable without some drawbacks. The results obtained from the assessment are discussed in the next section.

(a) Computational Burden

The factor of computational burden is hard to evaluate since the amount of data manipulation that must be conducted varies depending upon the various aspects, such as information requirements, parameters and iteration. This is attributed to the fact that the decision-maker's requirement for necessary information varies greatly from one method to another. Also, many different alternatives can be established for testing each method's sensitivity to the weights and effects. Thus, rather than attempting to evaluate all these aspects in the present analysis, the factor of computational burden will be examined with reference to the empirical analyses performed in the previous section.

Information requirements and computational efficiency. Of the three methods, none is clearly superior. The GAM, however, appears to be easier to use because the computational burden is modest compared to the other methods. However, the advantage of the GAM's straightforward approach may be offset by the quantity of information that must be assimilated by the analyst. To apply this method well, considerable resources are required for data collection and for adequate public participation.

While an analysis of various incidence sectors (the affected groups, classified by area, income, land use, etc.) to be affected by transportation projects has not been undertaken in this research, the GAM requires an impact evaluation of each of these various sectors. In particular, the sizeable amount of empirical work necessary to measure incidence of benefits and costs may be time-consuming, unless those impacts are large. The success of incidence analysis depends on the appropriate choice of sectors for analysis. The use of the GAM in the case reported here did not include a comprehensive consideration of sectors to be affected by transportation plans. Therefore, there is a danger that the GAM could prejudice the results by focusing on trivial incidence sectors and ignoring more important ones.

The CA places more demanding computational burdens than the GAM. Furthermore, the results obtained from the CA need still further analysis to be useful. The burden of information collection and assimilation on the analysts, and the information-processing burden on the decision-makers, is a clear disadvantage of the CA. It should be recalled that the CA begins with determining the weights to develop a full impact matrix, implying that prior computation must be performed with a technique such as the Churchman–Ackoff method. Each sensitivity analysis performed increases the amount of information to be absorbed just as it improves the multi-objective scope of the study (except in the happy instance where all results point the same way).

The computational burden of the CS is similar to that of the CA. The algorithms for developing nondominated sets involve substantial computation. An entropy calculation is quite time-consuming. In order to select the best alternative, compromise solutions through membership functions should be undertaken which require iterations. The CS also limits the analyst's scope by ruling out more intuitive approaches to the information. In effect, the method is too constraining on the analyst: it is hard to imagine a consultant to be merely a mixer of paints, as it were.

Possibility of sensitivity tests. The CA is superior for conducting sensitivity tests. The involvement of the decision-maker in the sensitivity tests in the CA is much easier than that of the GAM as the CA aims at a single or small number of decision-maker(s).

Sensitivity tests are potentially a difficult task because of the requirement of various public inputs. The GAM only provides results at the end of what is likely to be a very time-consuming process, and it cannot be readily fed back into the design of alternatives, which are assumed to be fixed. This is unfortunate, since following completion of the procedure the analyst usually has a great deal of specialised knowledge which could be fed back into the analysis. At this point in the decision-making process such modifications cannot be incorporated easily so that any extra information on the nature of various impacts, however potentially useful, is redundant.

The CS is attractive in terms of these criteria. In the CS, the decision is reached by an iterative process concentrating on sequential identification of 'bad' solutions. Sensitivity tests are likely to be burdensome, unless the computation is aided by computer programs.

Inclusion of qualitative information. Qualitative effects can be incorporated into the structure of each of the thee methods. The CA is particularly amenable to the inclusion of such effects, because it only requires statements as to the superiority or otherwise of one alternative over another, according to a certain criterion, regardless of the specific scale used to measure performance. However, an interval or ratio measurement scale is superior for the CA. An interval scale is particularly useful for deriving rankings among alternatives in the CA.

The GAM functions best in terms of incorporating qualitative information. The chief advantage of the GAM is its ability to accommodate and preserve qualitative information in a meaningful way. Also, full subjectivity of any formal weighting process relating to qualitative information is recognised. Any measurement scale can essentially be used in the GAM although Hill (1973) suggests that a ratio scale is preferable to an interval, and an interval scale to ordinally measured data.

The CS can easily accommodate qualitative information as long as it is expressed in terms of measurable units. A ratio scale seems to be the most useful scale for the CS because noncommensurable data (dollars, travel times, etc.) must be transformed into the degree of closeness to the ideal point.

(b) Degree of Interaction with the Decision-maker

None of the three methods is intended to substitute for human decision-making; all methods can be viewed as decision aids that synthesise the contents of the impact matrix into more essential and meaningful information.

Understandability of methods. Technical complexity may make the CA difficult for the decision-maker or layman to comprehend. This is a major drawback.

On the other hand, the GAM, can easily be both constructed by the analyst and understood by the decision-maker. One distinct advantage of the GAM is that its conceptual framework is simple and the underlying process of goals-achievement is comprehensible to the non-expert. Another advantage of the GAM is the lack of insistence on a 'bottom-line' recommendation to the decision-maker. While the results for the GAM reveal the best alternative, the method does not lead to a definitive statement of the best alternative.

The theoretical structure of the CS has similar drawbacks to those of CA in terms of communicating with nonexperts. Membership functions may be difficult to understand on the part of the decision-maker.

Encouragement of public participation. The CA and the CS are not appropriate for encouraging public participation. In these methods, public or administrative participation seems limited to an after-the-fact analysis review process, although it could be argued that public values are partially accounted for in the impact matrix.

The GAM appears to be the best way to encourage public participation. The GAM is designed to evaluate consequences across a broad range of community objectives. It could lend itself to participatory reviews, since all goals are preserved, and weights are simple to interpret. In developing goals, the analyst needs to consult elected officials and community groups, use public opinion sampling, and examine previous patterns of transportation investment.

Interaction requirements between the analyst and decision-maker. In evaluating the three methods with reference to this criterion, it is necessary to stress the stages of interactions between the analyst and the decision-maker. In contrast to the CA and CS, the decision-maker in the community to be affected by the transportation plans.

Figure 3 shows the differences among the three methods. The methods differ in the degree of value judgments required for deriving undominated solutions. The CA is attractive in terms of its interaction requirement between the analyst and the decision-maker. In the CA there is an opportunity for active involvement of the decision-maker at various stages in the procedure, including the specification of the objectives and criteria, and the determination of weights.

The GAM is a weak method with respect to these criteria. In contrast to the CA, the underlying philosophy of the GAM is the achievement of specified goals rather than the provision of information to the decision-maker. The GAM also is designed to cater for a variety of interest groups, making it difficult for the analyst to interact with multiple decision-making groups.

The CS can be regarded as a practical interactive method. It requires an active role on the part of the decision-maker throughout the analytical process. Instead of a rather passive position after helping to formulate a set of weights as in the case of the GAM, the decision-maker is deeply involved in the process of analysis.

(c) Real World Applicability

Applicability to auto-restraint types of transport projects. An inherent strength of the CA and the CS is that they have a potential applicability to a large number of alternatives. In this sense, the CA and the CS are useful for auto-restraint types of actions since a variety of similar but alternative types of auto-restraint schemes often exists within the urban transportation context.

The CA and the CS are also suitable for auto-restraint types of actions which can be regarded as being flexible and changeable because these methods can be put into operation quickly. Also, they are designed to be a short-term aid for the decision-maker, rather than a guiding framework for the transportation process as a whole.

One weakness inherent in the CA and the CS is that these methods are not effective in handling a large number of decision-makers. There is a wide variety of decision-makers involved in the decision-making environment surrounding auto-restraint policies. These decision-makers' perspectives are not coherent where each has his own preference function.

The GAM appears to be weak for handling auto-restraint transportation projects. The incidence sectors in terms of gains and losses between different interest groups do not seem to have been of importance for auto-restraint policies in the Seoul example. The incidence sectors are in general not incorporated into the planning and decision-making processes for auto-restraint policies. Also, the not inconsiderable effort involved in formulating objectives and weights may not be worthwhile for such small-scale, service-oriented transportation plans. The GAM is also of little utility when the effects of transportation projects themselves are minimal.

Applicability to capital-intensive transportation projects. In contrast to their usefulness for auto-restraint schemes, the CA and the CS are weak with respect to this criterion. The effects of capital-intensive transportation projects are generally considerable and complex. There is a danger in applying these methods that these effects may be aggregated in a crude way.

By definition, capital-intensive projects require large capital outlays, a longer time-span and a cost–benefit type of analysis. They may be successfully handled by a cost–benefit type of analysis in cases where such evaluation criteria as discount rates,

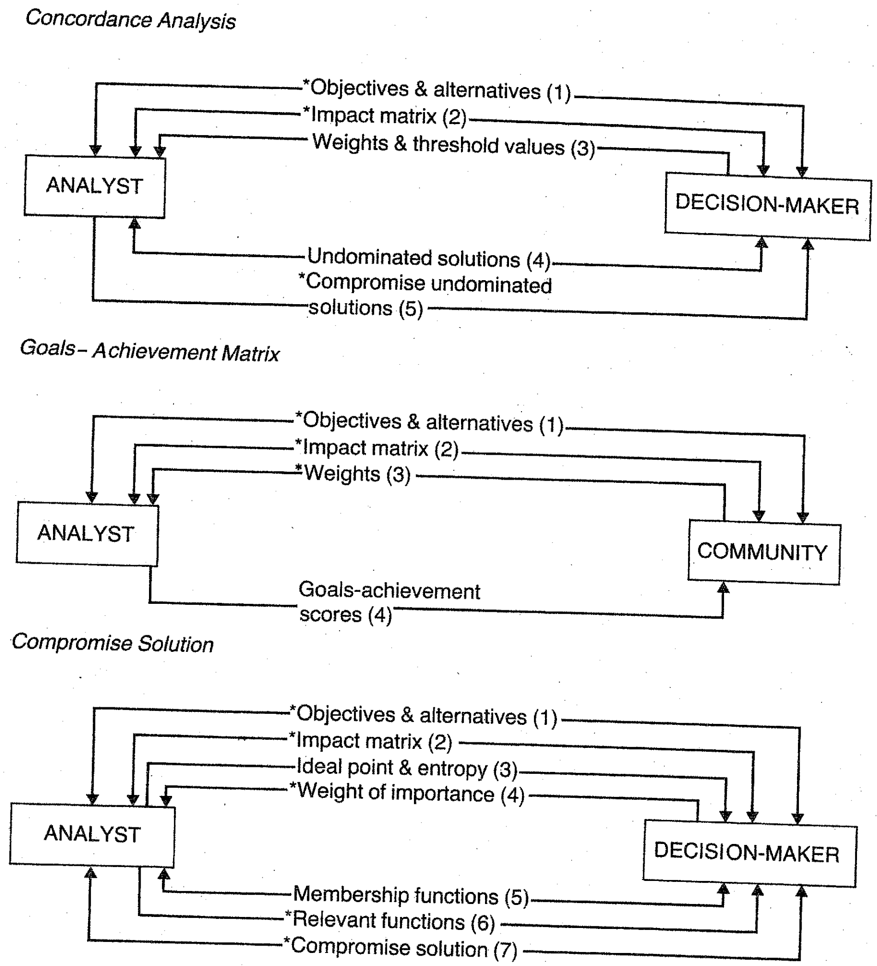

Figure 3. Stages of interactions between the analyst and the decision maker. (Elements marked by * are preceded by interaction between the analyst and the decision-maker.)

shadow prices, and opportunity costs are considered important. The CA and the CS can be used as a means to narrow down the number of capital-intensive projects when the above situation exists. After the number of alternatives is narrowed, an elaborate cost–benefit analysis can be employed for a systematic evaluation of a small number of alternatives.

While it is difficult to generalise on the nature of the decision-making environment surrounding capital-intensive projects, relatively fewer agencies and decision-makers are involved in making such decisions. Consequently, this environment is conducive to the underlying structure of the CA and the CS.

The GAM appears to be satisfactory for the capital-intensive transportation projects. Conceptually and practically it is more relevant than the other methods for analysing the effects of capital-intensive projects, because of its comprehensiveness. It provides a basis for incorporating all the relevant sectors that must be taken into account in the planning process. The GAM has a relative advantage in those cases where few alternatives are available, as is often the case with capital-intensive projects. In this sense, the underlying philosophy of the GAM is closely matched with the ongoing transportation practice of capital-intensive projects. The GAM would function best when sufficient time is available for formulating goals and weights. Major disavantages occur, however, when the area to be affected by the capital-intensive projects becomes large.

Incorporation of uncertainty. In the CA and CS, the problem of uncertainty is not properly addressed. These methods suggest performing sensitivity analyses for dealing with uncertainty. However, such analyses cannot handle effectively the uncertainty because of the dynamic nature of project effects and its complex computational demands. Since the underlying philosophy of these methods is the provision of information to the decision-maker on the 'one-shot' basis it appears difficult to incorporate uncertainty in a systematic manner.

The adaptability of the GAM may enable it to handle uncertainty better than other methods. It also recognises explicitly the difficulties inherent in uncertainty. The fact that the GAM is potentially capable of dealing with capital-intensive transportation projects is conducive to dealing with uncertainty since the latter can be generally considered important in such projects. In the GAM, project consequence (e.g. increase in travel time and environmental change) may be accompanied by probabilistic statements, or they may be expressed by a range of possible outcomes.

Linkage to planning process. The linkages to the overall planning process are weak in CA. CA can be employed at the stage of the selection of alternatives in the overall planning process. In this sense, the CA would probably not occupy more than a small part of the larger planning process if it were applied in the real world.

The philosophical basis of the GAM is more suitable for the overall planning process. The analyst doing the GAM is expected not only to formulate community objectives with the help of planners or decision-making groups, but also to evaluate selected alternatives. The active continuity of the analyst from the first stages of project design through to final evaluation is therefore essential.

The CS is not attractive with respect to the planning linkage criterion. It is a method of searching out the best solutions through interaction between the analyst and the decision-maker. Therefore, it is implicit in the CS that the analyst enters the planning process at a relatively late point, particularly at the stage of 'evaluation of alternatives'.

Linkages to decision-making process. The CA is satisfactory with respect to this criterion if there is only a single or a few decision-makers. If there are multiple decision-makers, this method is inferior because the alternative selection procedures and implementation are heavily influenced by many different decision-making groups in real-world situations.

The GAM is considerably more realistic about the decision-making process than are the other two methods. Even in the goal setting process, it tries to reflect the value structures of the diverse decision-making groups. Although the GAM suggests consultation with relevant agencies and a review of planning documents for setting the goals, intra- and inter-agency relationships stemming from the intersectoral nature of transportation projects could not be handled.

The CS is sensitive neither to the decision-making process nor to implementation. There is in fact no attempt to address the issues surrounding the decision-making process. Legal, administrative and financial considerations are hardly incorporated into the analytical process. This is a major limitation because the environment in which transportation planning takes place is characterised by the existence of important legal, administrative and financial constraints.

V. Conclusion

Summarising, it is clear that each of the three methods can be successfully implemented for transportation projects such as auto-restraint policies. Despite certain drawbacks, the multicriteria evaluation methods employed in this research have considerable potential as tools for assisting the decision-maker and others concerned with the transportation decision-making process. Their major advantage over traditional transportation evaluation methods is that they allow the consideration of a wider range of costs and benefits, and are oriented towards the decision-makers.

The empirical analysis also illustrates the usefulness of including qualitative criteria into the evaluation framework without transforming them to a monetary dimension. While the three methods have certain limitations that prevent complete confidence from being placed in their results, it is contended that the positive aspects of the three methods outweigh those disadvantages.

All of the methods can be viewed as decision aids that synthesise the contents of the impact matrices into more essential and meaningful information. The three methods are in general capable of incorporating the multicriteria imbedded in transportation plans. A brief summary of the assessment results follows.

(1) The GAM appears to be easiest to use because the computational burden is modest compared to the CA and CS methods.

(2) The three methods are in general capable of encompassing a variety of primary effects resulting from the implementation of transportation projects.

(3) The technical complexity inherent in the CA and CS seems to make these methods difficult for the decision-maker and layman to comprehend while the GAM can easily be constructed by the analyst and understood by the decision-maker.

(4) The CA is not relevant for encouraging public participation while the GAM appears to be the best approach to fostering such involvement. Because of the time-consuming and technical nature of the CS, its use is likely to be restricted to the analyst and key decision-maker.

(5) The CA and the CS are superior for testing sensitivity because these methods are designed to provide information to a single or few decision-maker(s). The GAM is weak in that it needs to include a variety of incidence sectors when reformulating goals and objectives and respecifying weights.

(6) The CA was found to be superior for ARA types of transportation projects due to its potential for assessing a large number of alternatives. The GAM is weak in its handling of auto-restraint schemes because the significant effort necessary to formulate objectives and weights from a wide range of incidence sectors may not be worthwhile for such small-scale and service-oriented transportation actions. The CS has a potential usefulness as a tool for screening a large number of transportation alternatives such as ARA types of policy.

(7) The linkage to overall planning process is weak in the CA and the CS while the philosophical basis of the GAM is more suitable for the overall planning process.

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