Ranking Highway Construction Projects: Comparison of Benefit-Cost Analysis With Other Techniques

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Three techniques for ranking highway construction projects are compared using 1,942 added-capacity projects. This is the first comprehensive comparison of ranking techniques using a large number of actual highway projects. The three techniques, (a) sufficiency ratings, (b) priority formula based on sufficiency ratings, and (c) benefit-cost analysis, are compared according to total benefits of project rankings for a fixed budget, rank correlation coefficients, and types of projects selected. For a 10-year budget for added-capacity projects of $5.742 billion, the benefit-cost procedure selects projects that provide more than $22 billion more benefits than does the sufficiency rating ranking, and about $7.8 billion more than does the priority formula. It is concluded that explicit use of a benefit-cost analysis maximizes benefits for a given highway budget. Also, a priority formula based on sufficiency ratings is much superior to use of the sufficiency rating alone. Because some version of sufficiency ratings is used to rank construction projects in most states, a large increase in benefits would result from using a priority formula or benefit-cost analysis.

In this paper, a comparison is made among three techniques for ranking major highway construction projects: highway sufficiency ratings, a priority formula based on highway sufficiency ratings and other factors, and a benefit-cost procedure (the modified HEEM–II program). Each technique is used to rank 1,942 added-capacity projects. This study is the first comprehensive comparison of ranking techniques using a large number of actual highway projects. The projects represent the list of candidate projects that the Texas State Department of Highways and Public Transportation is considering funding in the next 20 years. The list is limited to projects that expand highway capacity mainly through increasing numbers of travel lanes or through controlling access to the highway. A more detailed comparison of the techniques, as well as a comparison of six other ranking techniques have been published previously *(1)*.

The benefit-cost procedure used is described in the first section of the paper. The next four sections contain discussions of the sufficiency rating technique and the priority formula and also the results of a sensitivity analysis that was conducted to test the structure of these formulations. The sixth section contains the comparison of rankings using the different techniques, followed by conclusions in the final section.

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BENEFIT-COST ANALYSIS

The use of economic analysis in evaluating and comparing highway projects has been limited. A 1962 survey of state highway agencies by the Highway Research Board *(2)* revealed some use of benefit-cost analysis in most states but it was generally limited. A 1974 survey *(3)* revealed that 27 out of 39 states responding to the survey were using some sort of economic analysis. From the survey results, it was estimated that there was about a 10 to 20 percent increase in the regular use of economic analysis during the period from 1962 to 1974.

In recent years, with the limited funds for highway projects, more emphasis has been placed on getting a better return on the investment in highways. Economic analysis has provided valuable tools to examine the planning and policy questions confronting highway agencies; but unfortunately, there is not yet a consensus on the specific benefits or costs to be included in the analysis and the methods or assumptions used in calculating those benefits and costs.

In an effort to standardize benefit-cost analysis for highway improvement projects in 1977, AASHTO published a manual to calculate user benefits of highway and bus transit improvements *(4)*. Because of its red cover, it has become known as the *Redbook*. This manual provides a step-by-step procedure for analyzing a proposed highway project. The procedure can be time-consuming and subject to errors because it involves looking up numbers in tables, reading numbers from graphs, and performing numerous manual calculations.

Several computer programs have been written to reduce the time and errors in making manual calculations. The FHWA developed a computer program, called the Highway Investment Analysis Package (HIAP) *(5)*, which includes a comprehensive analysis of user benefits but is limited in examining alternative routes and requires large amounts of data.

Another computer program available for analyzing highway projects is the Highway Economic Evaluation Model (HEEM), originally developed in California and adapted for use in Texas *(6)*. The revised program, called HEEM–II *(7)*, compares the existing highway corridor with the corridor if the proposed improvements are made. (A corridor consists of the highway to be improved along with up to two alternate routes. The proposed highway can also be a new location construction.)

Traffic is allocated to each corridor highway based on motorist costs of travel on each route. Motorist costs, or user costs, are calculated for each year during an analysis period, typically

20 years. User costs consist of motorist time costs of travel through the specified corridor, vehicle operating costs, and accident costs. Costs are calculated for two vehicle types—passenger cars and trucks—on a daily basis. Daily costs are summed to a yearly total. This process is repeated and costs are discounted for each year during the analysis period.

The benefits of the proposed highway project represent the reduction in user costs (user costs on the existing corridor minus the user costs of the proposed corridor). The benefit-cost ratio is the user benefits plus any change in maintenance costs divided by the project cost. The benefit-cost ratio (B/C) is determined from

$$B = \sum_{t=1}^{n} (TC_t + VOC_t + AC_t + MC_t)(1 + r)^{-t} \quad (1)$$

where

C = project cost (construction cost plus right-of-way cost),
TC_t = reduction in time costs in year t,
VOC_t = reduction in vehicle operating costs in year t,
AC_t = reduction in accident costs in year t,
MC_t = reduction in maintenance costs in year t,
n = number of years in analysis period, and
r = discount rate.

Although HEEM–II represents an improvement over other models and techniques, especially in the explicit analysis of a corridor of highways, it has some limitations. First, HEEM–II is designed principally to analyze added-capacity type projects, generally adding one or more lanes to an existing highway. The program can analyze other types of projects, but with less precision. These include new-location projects when the existing corridor is poorly defined and upgrading deficiencies, such as widening lanes or adding shoulders. Second, the program uses daily traffic as the basis of analysis, so detailed analysis of congestion during the day cannot be performed.

For this study, a computerized program to analyze many added-capacity projects with limited data was needed. The HEEM–II program, which had the basic structure and characteristics required for the study, was modified somewhat so that it could run efficiently and with less data on a large number of added-capacity projects. The same output was generated—the ratio of the expected project benefits to the project costs. The expected benefits were calculated over a 20-year analysis period and an 8 percent discount rate was used. The assumed values of time per person in passenger cars and trucks are \$7.85/hr and \$19.20/hr, respectively. These are the default assumptions in HEEM–II *(7)*.

HIGHWAY SUFFICIENCY RATINGS

Highway sufficiency ratings are used to evaluate existing highways using engineering standards. These ratings are the outgrowth of procedures developed beginning in 1933 ". . . to describe on maintenance inspection reports the condition, safety, and service features of completed Federal-aid highway improvements that had deteriorated or become obsolete to the degree that reconstruction was warranted because of unduly high maintenance costs" *(8)*. In 1946 and 1947, the Bureau of Public Roads ". . . field tested a system for numerically rating the three elements of highway condition (structural, safety, and service) which would provide greater precision and uniformity and would permit complete coverage of the rural portions of the Federal-aid primary highway system." In 1947, Region IX of the Bureau of Public Roads adopted the rating plan that by 1951 was extended to the remaining division offices in the continental United States as a part of maintenance inspection procedures.

TABLE 1 DHPT SUFFICIENCY RATING FOR ADDED-CAPACITY PROJECTS

Category	Weights
Traffic flow conditions, present ADT volume on existing facility	
Good (LOS A-B)	0
Tolerable (LOS C-D)	7
Undesirable (LOS E-capacity)	14
Forced (1.0–2.0 × capacity)	21
Forced (more than 2.0 × capacity)	30
Traffic flow conditions, future ADT volume	
Good (LOS A-B)	0
Tolerable (LOS C-D)	6
Undesirable (LOS E-capacity)	9
Forced (1.0–2.0 × capacity)	12
Forced (more than 2.0 × capacity)	20
Present truck ADT volume per existing lane	
0–200	0
201–400	3
401–600	6
601–800	8
More than 800	12
Principal arterial system	
Off	0
On	5
Roadway functional classification	
Local or collector road or street	0
Minor arterial road or street	7
Rural principal arterials, urban connecting links of rural principal arterials, and other urban principal arterials	14
Interstate highways and other freeways	17
Gap considerations	
Does not eliminate capacity gap	0
Eliminates one-end capacity gap	9
Eliminates capacity gap on both ends or is system gap	16
Total sufficiency rating	100

Many state administrators faced with increased public demand for road improvements also adopted sufficiency ratings for state use. By June 1960, according to a Highway Research Board survey, 38 states used some type of sufficiency rating *(9*, p. 84).

Sufficiency ratings are an index usually consisting of three categories, each having several subunits with weights that typically sum to 100 points if the highway is totally sufficient. Highways with the lowest ratings are considered to be most in need of improvement.

The principal strengths of sufficiency ratings are that they are objective, easy to use, and easy to explain to the public. Sufficiency ratings have two principal weaknesses. First, because they originated from maintenance inspection reports, there has not been enough emphasis on capacity in rating highways that have deficient capacity and geometric standards. Second, the ratings are only a measure of the existing highway deficiency and do not indicate the benefit and cost associated with improvements to correct deficiencies.

Although many states have evaluated highways using sufficiency ratings, it is not clear how much these ratings have been used to set improvement priorities. Many states undoubtedly use other techniques and evaluations in addition to sufficiency ratings. The Texas Department of Highways and Public Transportation (DHPT) has not relied on sufficiency ratings as much as have other states. However, two different sufficiency rating schedules have been developed in Texas for possible use along with other evaluations in setting priorities. The Texas ratings are somewhat different from typical ratings. First, the rating schedules are set up so that the highways most in need of improvement are given higher ratings with a maximum of 100 points. Second, and more important, two different schedules have been developed, one for added-capacity projects (mainly adding lanes, providing medians, and controlling access) and one for upgrade-to-standards projects.

The Texas schedules represent a major improvement over typical schedules for purposes of setting priorities for added-capacity and upgrade-to-standards projects because they focus more on the categories of deficiency that would be affected by improvements. The added-capacity schedule emphasizes present and future capacity for the existing highway relative to present and forecasted traffic volumes. The upgrade-to-standards schedule focuses on items that cause the need for upgrading. The schedule for added-capacity projects is presented in Table 1 *(10)*. This sufficiency rating schedule gives points for deficiencies in the existing facility. Therefore, the ideal highway would receive 0 points and the most deficient possible highway would receive 100 points. Although it is more common for sufficiency ratings to go in the opposite direction—100 for the best facility and 0 for the worst—DHPT's method will be used in this paper because it is consistent with ranking techniques in which the higher the number, the higher the project priority.

In Table 1, the first two categories of traffic flow conditions are based on level of service (LOS). The table to convert average daily traffic (ADT) into LOS (presented in Table 2) is based on highway type and number of lanes. In the case of two-lane rural undivided highways, there is also a distinction for the type of terrain. The third category of truck ADT volume uses the current truck volume per lane on the existing highway instead of LOS. The next two categories are characteristics of the existing highway. The last category of gap considerations is the only category where the proposed project has any impact on the point total. The other categories are measures of the deficiencies on the existing facility.

TABLE 2 AVERAGE DAILY TRAFFIC VOLUME RANGES OF VARIOUS HIGHWAY CLASSES FOR VARIOUS QUALITIES OF FLOW

Highway Class	Range in ADT Service Volumes: Good Flow (LOS A–B)	Tolerable Flow (LOS C–D)	Undesirable Flow (LOS E–Capacity)
Urban freeways			
Four-lane	0–44,000	44,001–52,800	52,801–64,400
Six-lane	0–66,000	66,001–79,200	79,201–96,600
Eight-lane	0–88,000	88,001–105,600	105,601–128,800
Each additional lane	0–11,000	11,001–13,200	13,201–16,100
Urban divided streets[a,b]			
Four-lane	0–16,100	16,101–19,100	19,101–23,000
Six-lane	0–23,500	23,501–27,900	27,901–33,000
Eight-lane	0–29,400	29,401–34,900	34,901–42,000
Urban undivided streets[a,b]			
Two-lane	0–7,700	7,701–9,100	9,101–11,000
Four-lane	0–12,600	12,601–14,900	14,901–18,000
Six-lane	0–19,800	19,801–23,500	23,501–28,300
Rural Freeways			
Four-lane	0–20,800	20,801–31,600	31,601–42,000
Six-lane	0–31,200	31,201–47,400	47,401–63,000
Rural divided highways[a,b]			
Four-lane	0–12,000	12,001–17,500	17,501–35,000
Six-lane	0–18,000	18,001–26,200	26,201–52,500
Rural undivided highways[a,b]			
Rolling terrain, two-lane	0–2,800	2,801–4,700	4,701–14,700
Level terrain, two-lane	0–3,700	3,701–6,100	6,101–17,400
Level terrain, four-lane	0–9,500	9,501–13,000	13,001–26,000
Level terrain, six-lane	0–15,000	15,001–19,500	19,501–39,000

[a]A divided facility includes a flush or depressed median with sufficient width for storage of left turning vehicles. On undivided facilities, left turns are made from a through lane.
[b]Urban street, as opposed to rural highway, conditions prevail whenever the intensity of roadside development, speed zoning, signals, stop or yield signs, and so forth, result in interrupted flow conditions and reduced traffic speeds.

COST-EFFECTIVENESS TECHNIQUES BASED ON SUFFICIENCY RATINGS

Recognizing the shortcomings of sufficiency ratings for setting priorities for highway improvement, the FHWA and several states have developed other priority formulas. This type of technique is referred to here as a cost-effectiveness technique based on sufficiency ratings because the formulas represent a ratio of effectiveness to cost (or cost per highway or lane-mile). Effectiveness is measured by the change in the sufficiency rating between the existing and improved highways, multiplied by the annual ADT. The change in the sufficiency rating represents the effectiveness of the proposed highway improvement per vehicle mile and is weighted by vehicle miles to obtain total effectiveness. There are several variations of this general procedure, for example, the technique used by Minnesota *(11)*, the PRIPRO formula developed by FHWA *(12)*, and the cost-effectiveness procedure used in the Highway Performance Monitoring System *(13)*.

In this study, a similar technique was developed for testing in Texas. This technique is called the Texas priority formula because it is based on the Texas sufficiency rating and has features that distinguish it from formulations used elsewhere. The priority formula has two variations—one for added-capacity projects and one for upgrade-to-standards projects. The general equation for this priority formula is

$$PF = (SR_E - SR_P)(1 + P/100)(2CADT/3 + FADT/3)(LTH)/CST \quad (2)$$

where

- PF = priority formula rating,
- SR_E = sufficiency rating for existing facility,
- SR_P = sufficiency rating for proposed facility,
- P = sufficiency points for categories that do not change with improvement,
- $CADT$ = current annual average ADT,
- $FADT$ = forecasted, typically 20 years in the future, annual average *ADT*,
- LTH = project length (mi), and
- CST = initial highway construction and right-of-way cost ($ thousands).

The first factor in the priority formula represents the change in the sufficiency points as a result of the improvement. Because the Texas sufficiency ratings give higher point totals to more deficient highways, this change is obtained by subtracting the sufficiency rating for the proposed highway from the sufficiency rating for the existing highway. This change can be viewed as a proxy for the benefits of the project per vehicle. The second factor is an adjustment for those categories in the sufficiency rating that do not change as a result of the improvement and are, therefore, not reflected in the first term. In Table 1, these are shown as Categories 4, 5, and 6. The third factor is a weighted average of the current and future ADT. If the first two terms are viewed as adjusted benefits per vehicle, then multiplying by the total vehicles gives a measure of total benefits. The weighting of current and future ADT represents both the increasing number of vehicles over time and the lower present value of future benefits through discounting. The formula is then multiplied by project length and divided by project cost to produce a measure of the desirability of a project.

The Texas priority formula is not a benefit-cost ratio because the benefits are not measured in dollars. It is a cost-effectiveness index measuring the amount of benefits (or effectiveness) per dollar of construction cost. Each variation of the sufficiency rating presented in the next section can be used in the priority formula so there is a separate priority formula ranking associated with each sufficiency ranking.

ALTERNATIVE FORMULATIONS OF THE SUFFICIENCY RATING AND THE PRIORITY FORMULA

One weakness of an easy-to-use manual method of calculating a sufficiency rating, such as the Texas rating schedule presented in Table 1, is the limited number of different characteristics that receive points within each category. If a large number of projects is being ranked, many projects receive the same score. In a computerized version of the Texas sufficiency rating for added-capacity projects, the first three categories can easily be modified so the points are calculated directly using ADT. The points P_{ADT} for each of the first two categories in traffic flow conditions in Table 1 can be approximated using the following formula:

$$P_{ADT} = [(TRF - T1)/A1]^{A2}, \text{ if } T1 < TRF \leq T4 \quad (3)$$

where

- $A1$ = $\exp[\ln(T4 - T1) - \ln(S4)/A2]$,
- $A2$ = $[\ln(S4) - \ln(S2)]/[\ln(T4 - T1) - \ln(0.5T1 + 0.5T2)]$,
- TRF = ADT volume per lane on existing facility (either current ADT or future ADT),
- $T1$ = ADT/lane for upper limit on LOS A–B,
- $T2$ = ADT/lane for upper limit on LOS C–D,
- $T3$ = ADT/lane for capacity volume,
- $T4$ = ADT/lane for volume two times capacity,
- $S1$ = points for tolerable conditions,
- $S2$ = points for undesirable conditions, and
- $S4$ = points for forced flow greater than two times capacity.

Texas sufficiency rating points for ADT on urban freeways, along with the continuous approximations of those points using Equation 1 are shown in Figure 1. Each curve starts where the first points are awarded, intersects the midpoint of the second step, and stops at two times capacity where maximum points are awarded.

The points P_{TRK} for the truck ADT volume can be approximated using a simple linear equation.

$$P_{TRK} = 4.0 + 0.02(TK), \text{ if } TK > 200 \quad (4)$$

where TK equals current ADT truck volume per existing lane.

As shown in Figure 1, DHPT's sufficiency points for traffic flow conditions are given in such a fashion that the approxima-

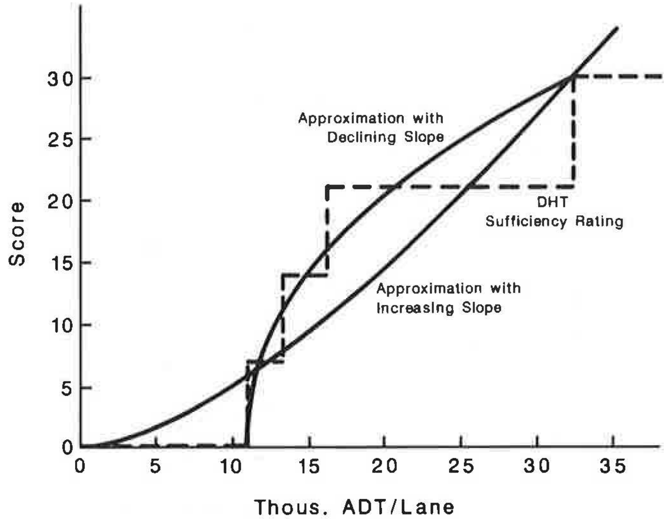

FIGURE 1 Continuous approximation of sufficiency rating scores for traffic flow condition categories as a function of average daily traffic per lane.

tion has a decreasing slope and the curve becomes flatter as ADT increases. If the points awarded are considered as proxy for the user costs generated by increased traffic volumes and congestion, the curve should have an increasing slope, with the curve becoming steeper as ADT increases. Therefore, a second modification was developed to approximate the points for both current and future ADT using the following equation.

$$P_{ADT} = [(TRF/A1)^{A2}], \text{ if } TRF \leq T4 \quad (5)$$

where

$A1$ = $\exp[\ln(T4) - \ln(S4)/A2]$, and
$A2$ = $[\ln(S4) - \ln(S1)]/[\ln(T4) - \ln(0.5T1 + 0.5T2)]$.

This equation starts at zero, goes through the midpoint of the first step in Figure 1, and stops at the maximum point at two times capacity.

An advantage of a sufficiency rating is that it is capped on both ends. In this case, points can only vary between 0 and 100. This limitation allows for an easy comparison of projects because each project can be compared with the best situation (0 points) and the most deficient situation (100 points). However, this system penalizes those projects that have conditions worse than the conditions necessary for maximum points in a category. In the case of ADT, existing facilities that have current or future ADT greater than two times capacity receive no additional points. As a result, the priority formula is also tested with no cap on points for those projects that have ADT values exceeding two times capacity.

SENSITIVITY ANALYSIS OF SUFFICIENCY RATING AND PRIORITY FORMULA

A pilot study of 102 proposed added-capacity projects throughout Texas was used to test and compare the variations of the Texas sufficiency rating and the Texas priority formula described in the previous section. Eight rankings were analyzed: the Texas sufficiency rating and three variations of it, and four priority formula rankings corresponding to each of the sufficiency ratings.

The various project rankings are first compared with each other using Spearman's rank correlation coefficient, which measures the degree of correlation between two sets of rankings. A coefficient of 1.00 indicates the rankings are the same, whereas a coefficient of −1.00 indicates they are the opposite. A coefficient of 0.00 indicates the rankings are not correlated at all. The correlation coefficient is calculated using the following formula, which includes an adjustment for ties *(14)*.

$$r = [M - (\Sigma D^2 + T_x + T_y)]/[(M - 2T_x)(M - 2T_y)]^{1/2}, \quad \text{with } -1 \leq r \leq 1 \quad (6)$$

where

r = Spearman's rank correlation coefficient,
M = $(n^3 - n)/6$,
D = difference in the pair of rankings,
n = number of projects,
T_x = $\Sigma(t_x^3 - t_x)/12$,
T_y = $\Sigma(t_y^3 - t_y)/12$,
t_x = number of ties in consecutive groups of the x series, and
t_y = number of ties in consecutive groups of the y series.

The comparisons of rankings using Spearman's rank correlation coefficient are presented in Table 3. The positive coefficients in the table indicate that all the variations produce rankings that are positively correlated, and the positive correlations are all statistically significant. Although no rankings are

TABLE 3 SPEARMAN'S RANK CORRELATION COEFFICIENTS FOR RANKING OF SAMPLE PROJECTS

	Code for Ranking Techniques						
	2	3	4	5	6	7	8
1	0.972	0.967	0.959	0.403	0.494	0.478	0.620
2		0.987	0.974	0.365	0.533	0.517	0.655
3			0.963	0.352	0.515	0.513	0.638
4				0.334	0.482	0.480	0.660
5					0.805	0.769	0.729
6						0.971	0.916
7							0.926

NOTE: All coefficients are statistically significant at the 1 percent level. The code for ranking techniques is defined as follows:

1. Texas sufficiency rating.
2. Texas sufficiency rating with continuous approximation for ADT and truck points.
3. Texas sufficiency rating with continuously increasing slope curves for ADT points.
4. Texas sufficiency rating with continuously increasing slope no cap on points.
5. Texas priority formula.
6. Texas priority formula with continuous approximation for ADT and truck points.
7. Texas priority formula with continuously increasing slope curves for ADT points.
8. Texas priority formula with continuously increasing slopes, no cap on points.

exactly the same (a coefficient of 1.00), the highest correlations are for rankings using modifications of the same technique between the sufficiency ratings and between the priority formulas. The Texas sufficiency rating (No. 1) and the three versions of it (Nos. 2, 3, and 4) have correlation coefficients greater than 0.96. The correlation between the priority formulas is generally not quite so high, with the correlation of the priority formula (No. 5) with the variations (Nos. 6, 7, and 8) ranging from 0.805 to 0.729, correspondingly.The correlations between Numbers 6, 7, and 8 are higher, ranging from 0.971 to 0.916, correspondingly.

The results of the pilot study rankings comparisons using the correlation coefficient indicate that the particular version of the Texas sufficiency rating used does not make much difference in project rankings. But that is not the case with the priority formula. Therefore, the original Texas sufficiency rating (No. 1) along with the last version of the priority formula (No. 8) were selected for further analysis on the complete set of added-capacity projects in DHPT's 20-year plan. The version of the priority formula with continuously increasing slopes and no cap on points, was chosen because it comes closest to representing the benefits generated by making an added-capacity improvement, which can then be compared with the cost of the project in making comparisons among projects.

COMPARISON OF PRIORITY RANKINGS

The three techniques discussed in preceding sections were used to rank a large number (1,942) of actual added-capacity projects that are being considered in Texas for possible funding in the next 20 years. These rankings are compared in three ways. First, the total highway user benefits obtained at different budget levels, or levels of cumulative initial cost, are compared for the three techniques; the improvement relative to random selection also is discussed. Second, a comparison is made of the rankings from different techniques to determine the extent to which the rankings are similar, using rank correlation coefficients. Third, a comparison of project rankings is made by deciles of cumulative initial cost to determine the location of projects being chosen (rural, urban, or suburban) and the average size of project selected.

Comparison of Benefits at Different Budget Levels

One of the principal criteria used to compare project rankings for the three techniques is the level of benefits provided by each technique's ranking. Two different sets of rankings were compared on this basis. First, a pilot study was conducted of rankings for 102 added-capacity projects, as reported in the preceding section. The complete test reported in this section involved ranking the full set of 1,942 added-capacity projects being considered for planned funding in Texas in the next 20 years. These 1,942 projects were ranked from first to last using each of the three techniques. The cumulative benefits were calculated using the modified HEEM–II computer program for the rankings using each technique. The results of this exercise are shown in Figure 2. Each technique's cumulative benefits are plotted versus the cumulative cost for that technique's rankings. In addition to showing the cumulative benefit curve for each of the three techniques, Figure 2 shows the cumulative benefits that would result from random selection (represented by the straight dashed line). The random selection line shows the benefits, at different levels of cumulative cost, that would be expected to result if projects were chosen randomly; the slope of this curve is determined by dividing the total benefits for all 1,942 projects by the total cost for all 1,942 projects, or $89.062 billion divided by $21.228 billion.

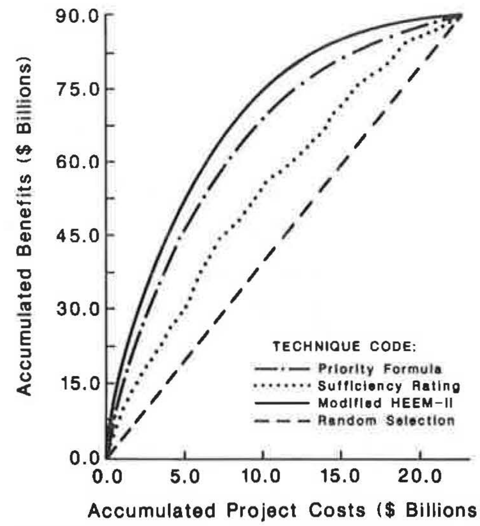

FIGURE 2 Cumulative benefits versus cumulative costs for rankings by different techniques.

All three ranking techniques show an improvement over random selection, with the HEEM–II benefit-cost technique having the highest cumulative benefit curve, followed by the priority formula and the highway sufficiency rating technique. All four curves eventually converge at the upper-right corner of the graph, representing the cumulative benefits and costs for all projects. A more precise comparison can be made, however, by comparing the benefits from each technique at lower budget levels. The data in Table 4 show such a comparison at budget levels representing funds that are expected to be available for budget levels for 1-year, 5-year, and 10-year construction programs. At the 1-year budget level of $0.785 billion, random selection of projects would entail selection of projects that

TABLE 4 CUMULATIVE BENEFITS AT SELECTED BUDGET LEVELS, BY TECHNIQUE

	Cumulative Benefits for Cumulative Cost		
Ranking Technique	$0.785 billion in 1-Year Program ($ billions)	$3.551 billion in 5-Year Program ($ billions)	$5.742 billion in 10-Year Program ($ billions)
Texas sufficiency rating	7.316	24.610	36.512
Texas priority formula	12.980	39.034	51.618
Modified HEEM–II	16.780	45.723	59.202
Random selection	3.293	14.898	24.091

provide \$3.293 billion in benefits as compared with \$16.780 billion for HEEM–II, \$12.980 billion for the priority formula, and \$7.316 billion for the sufficiency rating.

Perhaps more instructive is the benefit comparison at a 10-year budget level of \$5.742 billion. The percentage improvement over random selection at this budget level is shown for each technique in Table 5. The HEEM–II benefit-cost program selects projects that give 145.6 percent more benefits than does random selection. HEEM–II ranked projects for the 10-year budget are expected to give \$22.7 billion more than the sufficiency rating ranking and \$7.6 billion more than the priority formula ranking. It is not surprising that the HEEM–II technique gives the best ranking because these benefits are calculated using the HEEM–II estimates of savings in travel time costs, vehicle operating costs, and accident costs that are expected from these added-capacity projects. Nevertheless, the magnitude of the improvement is impressive. It should be noted that these benefits are calculated in terms of present values over a 20-year analysis period, assuming the projects are constructed immediately. Because the projects would be constructed over about a 10-year period, the assumption that they are constructed immediately has a tendency to overstate benefits. This overstatement would probably be more than offset by future traffic growth and benefits from the improvements, which are generated over a period greater than 20 years. Future research should include more precise calculations with phasing of the projects over time, allowing for traffic growth before the improvement is completed, and discounting future benefits from the time the projects are completed to the date considered. As noted, however, the estimated difference between techniques probably would increase from the consideration of the budget over time.

TABLE 5 TOTAL BENEFITS AND PERCENT IMPROVEMENT OVER RANDOM SELECTION FOR DIFFERENT TECHNIQUES FOR THE 10-YEAR PROGRAM (costing \$5.742 billion) OF ADDED-CAPACITY PROJECTS

Ranking Technique	Benefits for 10-Year Program (\$ billions)	Improvement Over Random Selection (%)
Texas sufficiency rating	36.5	51.5
Texas priority formula	51.6	114.1
Modified HEEM–II	59.2	145.6
Random selection	24.1	0.0

Rank Correlation Coefficients

Spearman's rank correlation coefficients were calculated for different pairs of rankings. The calculation technique used is similar to that in the pilot test discussed earlier, the only difference being that the full 20-year set of 1,942 added-capacity projects is used instead of the 102 projects in the pilot test.

Spearman's rank correlation coefficients between pairs of ranking techniques for rankings of 1,942 added-capacity projects are presented in the following table:

Ranking Techniques	*HEEM–II*	*Priority Formula*
Sufficiency rating	0.467	0.673
HEEM–II		0.806

These values can be tested to determine if the pairs of rankings are positively correlated. A rank correlation coefficient of only 0.053 is needed to reject the null hypothesis of no correlation or negative correlation at the 0.01 level of significance and of only 0.108 at the extreme 0.000001 test level. Because the smallest value in the table is 0.467, the hypothesis that the pairs of rankings are randomly related or negatively related is rejected and the hypothesis that the pairs of rankings are positively related is accepted.

Analysis of Location and Size of Projects Selected by Deciles of Cost

To further investigate the characteristics of projects being ranked highest by each technique, the rankings for each technique were divided into 10 groups (deciles) of roughly equal cost. To determine the projects in the first decile for a specific technique, the procedure used entailed going down the ranked list of projects until the next (marginal) project would cause cumulative cost to exceed one-tenth of the total cost of all projects. The second decile includes that marginal project plus all other projects down the list until the next project would exceed two-tenths of the total cost of all projects, and so forth. There are some small differences between the costs of each decile because of projects that do not add precisely to one-tenth. Also, in the case of sufficiency ratings, there are some project ties in the ranking. All of the ties are put in the same decile so there is more irregularity in the decile costs for sufficiency ratings than for the other techniques.

Within each decile, for each ranking technique, several characteristics are evaluated. The characteristics of all 1,942 added-capacity projects are summarized in Table 6. Less than one-third of all projects are in urban areas but these projects represent almost 50 percent of all project costs. The urban-rural fringe area projects represent 20.7 percent of all projects and only 13.8 percent of all costs. Rural projects represent 48.1 percent of all projects but only 36.5 percent of all costs.

TABLE 6 CHARACTERISTICS OF 1,942 ADDED-CAPACITY PROJECTS CONSIDERED AS POSSIBILITIES FOR FUTURE CONSTRUCTION

	Type of Area			
Characteristic	Urban	Urban-Rural	Rural	Total
Number of projects	605	402	935	1,942
Percent of all projects	31.2	20.7	48.1	100.0
Cost of projects (\$ millions)	10,542	2,934	7,752	21,228
Percent of all cost	49.7	13.8	36.5	100.0
Average cost per project (\$ millions)	17.4	7.3	8.3	10.9

TABLE 7 TOTAL COST OF URBAN PROJECTS SELECTED BY EACH TECHNIQUE BY DECILE OF TOTAL COST

Technique	Decile of Total Cost ($ millions) 1	2	3	4	5	6	7	8	9	10	Total ($ millions)
Sufficiency rating	1,726	1,670	1,258	1,312	1,263	1,345	699	659	496	114	10,542
Priority formula	1,249	1,338	1,382	1,220	1,228	968	1,134	792	671	559	10,542
Modified HEEM–II	972	870	1,083	1,147	841	694	1,277	1,316	1,080	1,261	10,542
Average	1,314	1,293	1,241	1,226	1,111	1,002	1,037	2,767	749	645	10,542

TABLE 8 TOTAL COST OF URBAN-RURAL FRINGE PROJECTS SELECTED BY EACH TECHNIQUE BY DECILE OF TOTAL COST

Technique	Decile of Total Cost ($ millions) 1	2	3	4	5	6	7	8	9	10	Total ($ millions)
Sufficiency rating	257	373	403	425	83	172	342	315	206	358	2,934
Priority formula	538	540	294	284	295	124	182	253	150	275	2,934
Modified HEEM–II	589	671	338	359	235	208	183	94	210	45	2,934
Average	461	528	345	356	204	168	236	221	189	226	2,934

TABLE 9 TOTAL COST OF RURAL PROJECTS SELECTED BY EACH TECHNIQUE BY DECILE OF TOTAL COST

Technique	Decile of Total Cost ($ millions) 1	2	3	4	5	6	7	8	9	10	Total ($ millions)
Sufficiency rating	107	108	463	378	674	694	1,085	1,167	1,426	1,650	7,752
Priority formula	330	251	288	733	631	1,027	829	1,072	1,300	1,291	7,752
Modified HEEM–II	517	612	679	642	1,031	1,204	707	677	864	819	7,752
Average	318	324	477	584	779	975	874	972	1,197	1,253	7,752

The data in Tables 7 through 9 present the costs of projects selected by each technique by deciles of total cost for urban areas, urban-rural fringe areas, and rural areas, respectively. The sufficiency rating tends to select large urban projects in the top deciles but distributes urban-rural fringe projects more evenly over deciles. Large urban projects tend to be ranked high because they have large traffic volumes and, thus, large sufficiency ratings, and the sufficiency rating does not adjust this for larger construction costs in urban areas. This effect carries over somewhat into the priority formula. The modified HEEM–II tends to provide a more uniform distribution across deciles. The priority formula and HEEM–II tend to favor urban-rural fringe area projects much more than does the sufficiency rating.

The data in Table 10 show the percentage of project costs summed over the first three deciles in Tables 7 through 9. These top three deciles cover a total project cost of about $6.368 billion, or slightly more than is anticipated will be available for these types of projects in the next 10 years, so these three deciles cover the projects that are of most interest in developing a 10-year plan.

The sufficiency rating and priority formula both allocate a large percentage of the total budget (for the first three deciles) to urban projects, with 73.1 and 63.9 percent, respectively, as compared with HEEM–II's 46.2 percent. The priority formula and HEEM–II both allocate a relatively high percent to suburban (urban-rural) projects, with 22.1 and 25.2 percent, respectively, as compared with an average of 13.8 percent for this type of project for all projects. All three techniques allocate a smaller percent than the overall average to rural projects, but the sufficiency rating and priority formula are especially low with 10.7 percent and 14.0 percent, as compared with 36.5 percent for all projects. HEEM–II is much closer to the overall average with 28.6 percent of all costs allocated to rural projects.

CONCLUSIONS

The priority formula ranking for the 10-year budget provides considerably more total benefits than does the sufficiency rat-

TABLE 10 PERCENTAGE DISTRIBUTION OF NUMBER OF PROJECTS IN TOP THREE DECILES BY TYPE OF AREA, BY TECHNIQUE

Technique	Percentage Distribution of Number of Projects in Top Three Deciles by Type of Area: Urban	Urban-Rural	Rural	Total
Sufficiency rating	64.0	20.2	15.7	99.9
Priority formula	52.4	24.9	22.7	100.0
Modified HEEM–II	35.6	27.2	37.2	100.0
Average	50.7	24.1	25.2	100.0
Average (all deciles)	31.2	20.7	48.1	100.0

ing ranking. For a 10-year expenditure program, the priority formula gives 114 percent more benefits than does random selection and 41 percent more benefits than does the sufficiency rating. This finding indicates that the priority formula, by considering the change in the sufficiency rating, by weighting the change in rating by vehicle-miles of travel, and by dividing effectiveness by project cost, transforms the sufficiency rating into a greatly improved rating method. This implies that the Texas sufficiency rating schedule does a good job of measuring the factors that affect benefits, but that the schedule must be used properly in a priority formula to become a good ranking technique.

The benefit-cost analysis is superior to both the sufficiency rating and the priority formula in maximizing motorist benefits. For the 10-year construction program, the benefit-cost analysis gives 62 percent more benefits than the sufficiency rating and 15 percent more benefits than the priority formula. This represents an increase in benefits of $22 billion relative to the sufficiency rating and $7 billion relative to the priority formula.

Because some version of sufficiency ratings is used to rank construction projects in most states, it is concluded that a large increase in benefits would result from using a priority formula or benefit-cost analysis.

ACKNOWLEDGMENTS

This paper is based on a study performed by the authors for the Texas Department of Highways and Public Transportation. It was prepared in cooperation with the FHWA, U.S. Department of Transportation, and is the result of a cooperative research effort. The authors are indebted to members of the Texas Department of Highways and Public Transportation, Design Division (D–8), and the Study Advisory Committee for their assistance throughout the study. Bryon Blaschke, formerly head of D–8 and now assistant director, was instrumental in setting up the study. Frank Holtzmann, current head of D–8, and other D–8 staff members assisted researchers throughout the progress of the research on which this paper is based. The authors are especially indebted to Harold Conner for his special input and assistance throughout that research. Billy Rogers of D–8 and Bubba Williamson, formerly with D–8, also assisted with and made contributions to the research.

The authors are indebted to Margaret Chui, who assisted with computer analyses, and Pat Holmstrom, who assisted with the study and typed this paper.

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Publication of this paper sponsored by Committee on Application of Economic Analysis to Transportation Problems.