New Approach to Integrating Engineering, Managerial, and Political Judgment: Development of the Utah Project Prioritization System

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The findings from a research project sponsored by the Utah Department of Transportation (UDOT) between 1989 and 1991 are presented. The goals of the project were to document, formalize, and improve UDOT procedures for prioritizing highway projects. The methods presented here and tentatively adopted by UDOT involve a relatively new approach that integrates and extends traditional engineering measures of reliability in the context of a management science model of productive efficiency. The political priorities of decision makers can be incorporated directly into the model in terms of explicit weights on the relative importance of each dimension being evaluated. In addition, the framework provides a means of assessing the cost of ad hoc revisions in the priority listing.

The deterioration of the level of service offered by the nation's transportation system has become a serious concern. Clearly, pavements and other highway elements make up a significant portion of that infrastructure. Currently, the need for transportation improvements is occurring faster than funds for improvements are being made available. As a result, state departments of transportation (DOTs) face the problem of allocating insufficient funds among numerous highway projects. The Utah Department of Transportation (UDOT) is not immune to these problems. This paper reports the results of a research project carried out in conjunction with UDOT. The purpose of the project was to document and recommend improvements in the procedures used by UDOT in selecting and funding highway projects and to recommend improvements in those procedures (*1*).

In 1989, UDOT's project selection process was largely informal. Consequently, as UDOT staff responded to pressures from local transportation districts, citizen groups, the press, and other public agencies, they often felt vulnerable and unable to convincingly defend their project decisions. Further, when priorities were changed by political forces within the state, it was difficult to assess the effect of these changes on the highway system.

Like any other state, the task of prioritizing highway projects in Utah is both technically complex and politically sensitive. The search for alternative methods of prioritization was guided by these realities. The comparative review of other states focused on how those states systematically program transportation projects within the context of their own technical and political complexities. In pavement management systems, for example, there are commonly five different techniques that are employed in selecting resurfacing and rehabilitation projects:

1. Sufficiency ratings (*2,3*),
2. Quasi-economic analyses (*2,4*),
3. Cost-benefit analysis (*2,4*),
4. Micro- or macro-economic analyses (*2*), and
5. Optimization techniques (*5–9*).

Pavement management systems have been proposed that utilize more than one decision model, often employing at least one kind of optimization technique. One such proposal, termed the "Demand Responsive Approach to Highway and Maintenance Rehabilitation," has been developed through the Department of Civil Engineering, the Massachusetts Institute of Technology (*10*). Another approach that employs optimization techniques along with other decision models has been developed by the Purdue University Department of Civil Engineering in conjunction with the Indiana Department of Transportation and FHWA (*11*). For its bridge management system, the state of Indiana separately utilizes both a ranking model and an optimization model. The ranking model was developed using the analytic hierarchy process technique (*11*).

Another method of optimization is data envelopment analysis (DEA). DEA is a recently developed methodology for measuring the relative efficiency of a set of decision-making units. The seminal paper in DEA was written by Charnes et al. in 1978 (*12*). Since that time over 300 papers have appeared on the topic of DEA (*13*). Although it is not currently used in state transportation agencies, the methodology is nevertheless an extremely useful decision model for prioritizing and programming transportation projects.

DEA was recommended to UDOT as the basis for prioritizing projects. It has strong theoretical foundations, provides the project-level evaluation that is required, and can be fairly readily implemented. Although DEA is not immune to criticism, the same can be said for virtually any approach to the prioritization problem. Each approach has both strengths and weaknesses, but DEA appears to offer great potential for

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addressing the questions raised by UDOT while minimizing other detracting factors. The remainder of this paper details how DEA can be used as the basis for prioritizing and programming transportation projects. The next section outlines the conceptual basis for DEA and explicitly specifies the DEA models. Next, the use of DEA is demonstrated with 49 projects that were either constructed or seriously considered by UDOT. Finally, the integration of DEA into transportation decision making, illustrated by the specific case of UDOT, is discussed.

SPECIFICATION OF DEA MODELS

As discussed previously, the task of prioritizing highway projects in Utah takes place within a context that is technically complex and politically sensitive. To be useful, the prioritization model should to the extent possible reflect and incorporate this complexity and sensitivity. This discussion will begin by focusing on the technical aspects of the problem; political issues will also be introduced.

The major technical components to be included in the model are as follows:

1. *Degradation function (DF).* A functional description that reflects effects such as load, weather, and traffic on existing conditions (EC) and describes the expected deterioration over time without treatment (T). Most researchers agree that DF is relatively flat for some initial period of life and then begins to increase at a growing rate. At some point, performance drops below a minimally acceptable level. The age of the roadway at that point of failure sets the upper limit for expected years of life for a new roadway. DF allows the estimation of both the need for and the impact of any given treatment on a particular segment of road.
2. *Existing conditions.* Central to the modeling effort is a description of current roadway conditions around the state. EC can be described with a large list of indicators, but it is reasonable to group those indicators into five dimensions of concern:

   a. Level of service—the traffic and load-carrying capacity of the existing road;
   b. Pavement condition—the surface and subsurface conditions of the pavement;
   c. Condition of structures—the condition of bridges or other major structures involved in the project;
   d. Ride—the quality of the roadway from the user's perspective; and
   e. Safety—frequency and severity of accidents.

For the first four dimensions a measure of remaining service life (RSL) or expected years until an unacceptable level of performance is reached can be estimated given existing conditions and the rate of deterioration. Another indicator of need relevant to the first four dimensions is the number of persons served by the roadway in question. To assess the safety dimension, the number and severity of accidents are compared with expected values for similar roads.

3. *Treatments.* The types of projects that might be performed on any given roadway and that operate to mitigate the degradation effects (DF). The issue is how T will improve the level of service, pavement condition, structures, ride, and safety. For level of service, pavement, structures, and ride, this measure of improvement is captured in the additional years of service life (SL) that will result from the project. Again using the degradation function, it is possible to calculate the years of additional life generated by the project and thus a new RSL. To evaluate improvement in safety, the expected reduction in accidents and accident severity is used.
4. *Cost per unit of treatment (C/T).* Preliminary estimates of unit costs for each type of treatment. Project costs can be characterized broadly in terms of UDOT in-house costs, direct contract costs, and user costs resulting from the project.

Each potential project (or project alternative if several alternatives exist for a given site) is thus characterized in terms of need, improvement, and cost variables. The conceptual framework used here assumes that existing conditions (EC) at time *t* are degraded according to the degradation function (DF). This degradation is mitigated by some treatment. The total costs of the treatment are generated from treatment quantity (T) and the C/T. Conditions at time $t + 1$ result from the interaction of EC, T, and DF.

Figure 1 demonstrates graphically the concepts introduced so far. The vertical axis, labeled *PSI*, represents the present serviceability index or any other measure of roadway conditions. The horizontal axis is time in years. The hypothetical current condition is shown as a dashed line. Given the degradation function, knowing the current service level allows the calculation of the remaining years of life and thus the need for any project. Although Figure 1 shows a single degradation function, a transportation project may change the shape of the function itself. Even if this is true, years of remaining life and years of additional life added by the project remain the relevant indicators of need and improvement, respectively.

Not all dimensions of a given project proposal are under direct managerial control, and this fact must be reflected in the model. Consider, for example, a project to resurface a pavement. In the short run, management has no control over the need for such a project. The level of improvement and the project costs, on the other hand, are under direct managerial control because the scope of the project can be modified and the particular strategy pursued can be changed. The point is simply that the model must show that need is not subject to managerial control, whereas cost and improvement are.

In implementing the approach proposed here, one must also be cognizant of the meaningful direction of the numeric

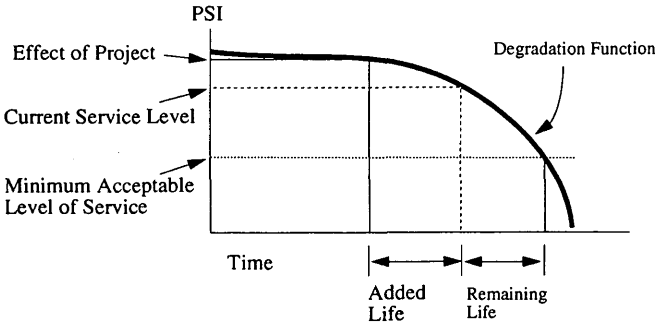

FIGURE 1 Service degradation and measures of need and improvement.

scales used. For example, if the need for a project is measured in terms of expected years of life remaining, then the larger the value, the less the need for attention. If on the other hand the need is measured in terms of traffic volume served, then the larger the number, the greater the need. Both approaches are quite reasonable, but the analyst must keep in mind for each variable in the analysis whether greater attention should be paid to small values or large.

Table 1 summarizes this discussion and lists the variables used in the initial implementation of the model. The table indicates whether the variable is a measure of need, improvement, or cost; whether it is interpreted as being under direct short-term managerial control; and whether large or small values will be emphasized. Variables over which management has no control are considered nondiscretionary and are labeled with an *N*. Variables scaled so that small values should receive greater emphasis are considered inputs and are labeled with an *I*, whereas the converse are considered outputs, labeled with an *O*.

We now turn to a more precise discussion of the DEA model originally outlined by Charnes et al. (*12*). The particular formulation outlined here follows Adolphson et al. (*14*). Data for DEA consist of a set of input measures $X = [x_{ki}]$ and a set of output measures $Y = [y_{kj}]$, where x_{ki} is the amount of input i consumed by project k and y_{kj} is the amount of output j produced by project k. Let $u_j = [u_1, \ldots, u_J]$ and $v_i = [v_1, \ldots, v_I]$ be the vectors of output and input weights. Then the linear programming models to choose weights for a given project, indexed by k, are either of the following:

$$
\begin{array}{lll}
\textit{Input Orientation} & \textit{Output Orientation} & \\
\text{Maximize} & \text{Minimize} & \\
\sum_j u_j y_{0j} & \sum_i v_i x_{0i} & (1) \\
\text{Subject to} & & \\
\sum_i v_i x_{0i} = 1.0 & \sum_j u_j y_{0j} = 1.0 & (2) \\
\sum_j u_j y_{kj} \le \sum_i v_i x_{ki} \quad \text{for all } k & \sum_i v_i x_{ki} \ge \sum_j u_j y_{kj} \quad \text{for all } k & (3) \\
u_j,\ v_i \ge 0 \quad \text{for all } i \text{ and } j & u_j,\ v_i \ge 0 \quad \text{for all } i \text{ and } j & (4)
\end{array}
$$

The duals of the LP models above are computationally more efficient and have a natural interpretation that sheds additional light on the process of DEA:

$$
\begin{array}{lll}
\textit{Input Orientation} & \textit{Output Orientation} & \\
\text{Minimize} & \text{Maximize} & \\
\Theta & \Theta & (5) \\
\text{Subject to} & & \\
x_{0i}\Theta \ge \sum_k x_{kj}\lambda_k \quad \text{for all } i & x_{0i} \ge \sum_k x_{ki}\lambda_k \quad \text{for all } i & (6) \\
y_{0j} \le \sum_k y_{kj}\lambda_k \quad \text{for all } j & y_{0j}\Theta \le \sum_k y_{kj}\lambda_k \quad \text{for all } j & (7) \\
\lambda_k \ge 0 \text{ for all } k & \lambda_k \ge 0 \quad \text{for all } k & (8)
\end{array}
$$

TABLE 1 Variables Used To Describe Projects in Initial Implementation of DEA Model

Dimension of Concern	Measures of Need	Improvement and Resource Measures
Level of Service	Expected years until actual traffic volume exceeds acceptable level of service (NI)	Additional years added by project until traffic volume exceeds acceptable level of service (O)
	Current Average Daily Traffic (ADT) volume (NO)	Expected change in total traffic (annual ADT) over a 20 year period (O)
	Design Hourly Volume (20 year) (NO)	
Pavement condition	Years of pavement life remaining (NI)	Additional years of life added (O)
	Surface conditions: a. rut depth (NI) b. index of cracking (NI) c. skid index (NI)	Surface conditions: expected improvement resulting from the project. a. rut depth (O) b. cracking (O) c. skid (O)
	Average daily ESALs (NO)	
Ride	Expected years to ride failure (NI)	Estimated additional years of ride life resulting from project. (O)
Condition of Structures	Years until adequacy of structure falls below acceptable standard 1) deck (NI) 2) structure (NI) 3) deck geometry (NI) 4) sub-structure (NI)	Additional years added by project: 1) deck (O) 2) structure (O) 3) deck geometry (O) 4) sub-structure (O)
Safety	Ratio of actual accident rate to statewide accident rate for similar roads (3 year average) (NO)	Expected reduction in accidents as a result of project (3 year average) (O)
	Ratio of actual severity index to statewide severity index for similar roads (3 year period) (NO)	Expected change in the severity index (3 year average) (O)
	Number of accidents occurring over the past 3 years (NO)	
Resources required		Direct project costs (I)
		Indirect UDOT costs (I)
		Estimated user costs during construction (I)
Other relevant factors		Length of project in miles (O) (Optional, used when projects being evaluated have meaningful length)

The input-oriented model contracts input as far as possible while controlling for outputs; the output model expands output as far as possible while controlling for inputs. In both cases, Θ is the contraction or expansion factor, and λ is a vector of weights that defines a comparison point on the frontier. For this discussion the focus will be on the input orientation.

Banker and Morey (*15*) show how to incorporate environmental or nondiscretionary inputs and outputs into a DEA model. Environmental input constraints are shown in Equation 6 for the output orientation, and environmental outputs are shown in Equation 7 for the input orientation. The effect of the nondiscretionary inputs is to limit the feasible comparison points to those with an input less than or equal to the corresponding input for the reference unit being evaluated. The effect of the nondiscretionary outputs is to limit the feasible comparison points to those with an output greater than or equal to the corresponding output for the reference unit.

The basic DEA models, Equations 1 through 4, are unrestricted in selecting nonnegative input and output weights. This approach frees the model user from the necessity of assigning relative weights to inputs and outputs; it also prevents the user from having any control over these weights. Consequently, the model is unable to reflect the political realities of the decision-making process. Fortunately, DEA allows the model user to specify bounds on the relative weights of inputs and outputs. The term "assurance region" was coined by Thompson et al. (*16*) to describe a feasible set of attribute weights. Consider the example of an assurance region in which the model user determines that input i is at least twice as important as input j. This implies that $v_i/v_j > 2$, or $v_i - 2v_j > 0$, in equivalent linear form. The equivalent linear form can be appended to Equations 1 through 4 or it can be expressed as a dual variable and included in Equations 5 through 8. Charnes et al. have given an alternative specification that multiplies the input and output matrixes by the matrix of attribute value constraints. Instead of assurance region, Charnes et al. (*17*) use the term "cone ratio" for the feasible set of weights. By specifying assurance regions or cone ratios, the user can incorporate a significant political component of decision making—the ranking and prioritizing of goals—into the DEA model.

A simple numerical example is now given that permits the discussion of the DEA-based method pictorially. In this example, two measures of outcome and one of input are considered. The measure of improvement is the years of additional life added by the project. A second variable, project length, is intended to reflect the scale of each project. A single measure of cost in thousands of dollars is also provided. These variables for five hypothetical projects are summarized in Table 2, along with the ratio of output per unit cost.

Figure 2 is a graph of the two ratios from Table 2. From both the table and the graph it can be seen that Projects B and C represent the most productive projects in this set. Project B is in the most productive set because it is the largest project per unit cost, and C, because it offers the greatest improvement per dollar spent. The convex envelope defined by Projects B and C thus sets the standard for most productive projects. This envelope is referred to as the best practice frontier. Project A is evaluated by extending a line from the origin through *A* until it intersects the frontier defined by *C* and the convexity assumption. The productivity score for *A* is obtained by taking the ratio OA/OA′ with the result of 0.525. The interpretation of this score is that *A* is slightly more than half as productive as *C*. For *A* to be on the frontier, either project costs would have to be reduced by a factor of 0.525 or improvement and length would have to be increased by a factor of 1/0.525 without changing the cost. A similar story could be told for Projects D and E, with resulting scores of 0.450 and 0.525, respectively. The scores for all five projects are summarized in Table 2 as PPS Score 1.

Reconsider the frontier defined by *B* and *C*. One could readily argue that although it is important to consider project length in evaluating and comparing projects, length of project is certainly not as central to UDOT's mission as is overall improvement to the highway system. Figure 3 shows the new frontier if it is assumed that improvements to the highway system are at least twice as important as the length of the project. Note that whereas Project B was on the frontier in Figure 2 by virtue of having the lowest cost per unit length, in Figure 3 Project B is well off the frontier. Setting the bound or assurance region for the trade-off rate between improvement and size (i.e., improvement is at least twice as important as length) prevents the slope of the frontier from falling below the point labeled *B′* in Figure 3. The revised scores for the five projects are in the last column of Table 2. The resulting score for Project B is 0.611. Notice also that the score for Project D also has changed because the frontier against which it is compared is now different. Project C remains on the frontier and is now the only project on the frontier. Because Projects A and E are still compared only with Project C, the scores for these projects also remain unchanged. Thus the subjective assessment regarding the relative importance of improvement and length has added materially to the analysis.

Score 1 reflects primarily engineering and managerial judgment. Score 2 incorporates political assessment of the relative importance of improvement and project size (i.e., improve-

TABLE 2 Data for Numerical Example and DEA Results

Project	Change in RSL	Project Cost	Length	Length/Cost	Improvement/ Cost	PPS Score # 1	PPS Score # 2
A	3	80	0.2	2.5	37.45	0.525	0.525
B	5	120	1.0	8.3	41.67	1.000	0.611
C	5	70	0.5	7.1	71.43	1.000	1.000
D	8	800	3.0	3.7	10.00	0.450	0.158
E	6	160	0.6	3.7	37.45	0.525	0.525

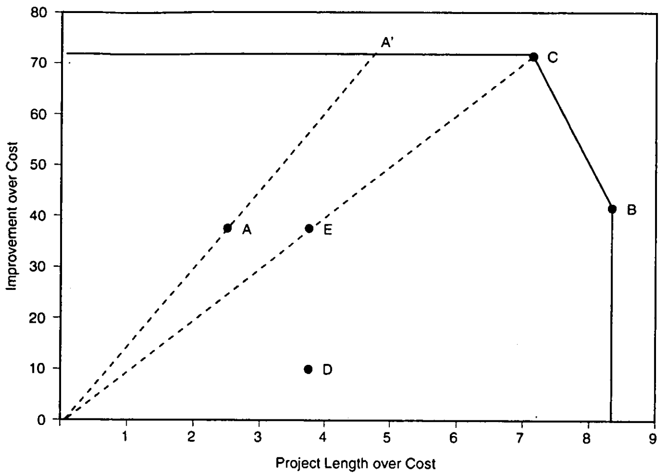

FIGURE 2 DEA Example 1: improvement and length weighted equally.

ment is at least twice as important as size). The DEA-based method proposed here suggests then that projects should be prioritized on the basis of either Score 1 or Score 2 in Table 2, and those with higher ranks should be constructed first. How far the agency is actually able to move down the priority list is a function of funding levels.

Although this simple example was constructed using only two outcome measures, DEA is quite capable of incorporating multiple dimensions as well. A richer demonstration was performed for UDOT to illustrate this more clearly.

DEA DEMONSTRATION USING REAL PROJECTS

To demonstrate the methods, data were obtained from UDOT on 49 projects that either have been recently approved for construction or are currently in design. The project sites lie throughout the state and reflect a broad range of both project size and diversity of scope. Projects included range from relatively small safety improvement proposals to major reconstruction and even new construction. In some instances, UDOT was able to provide reasonable data for current service levels but was unable to provide estimates of remaining service life. In these cases, reasonable but very simple assumptions were made regarding the rate of degradation over the design life for a particular variable. The assumptions yield plausible results that are adequate for this demonstration, even though actual values may vary from those used here.

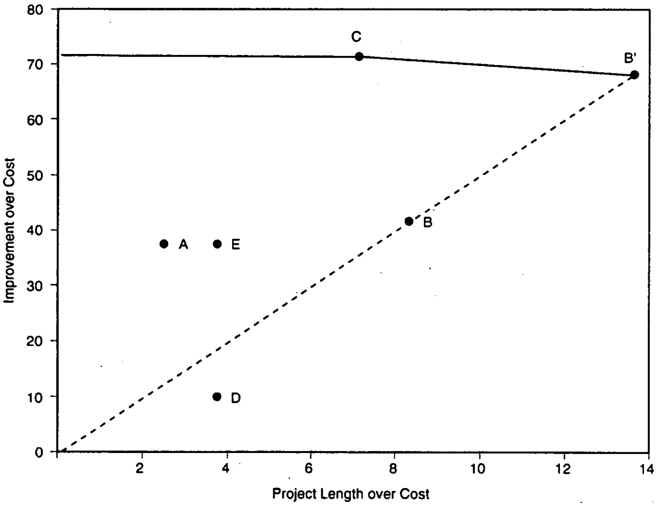

FIGURE 3 DEA Example 2: improvement at least twice as important as length.

To facilitate the demonstration, the projects were first broken down into four categories, on the basis of the expected project components. The categories are

1. Capacity,
2. Safety,
3. Pavement, and
4. Bridge structures.

In the full demonstration, a separate analysis is provided for each class of projects, followed by an integrated analysis including all projects. For the sake of brevity, only the pavement analysis and overall analysis are reported here. The complete demonstration report is available from the authors (*1*).

Pavement

For the pavement part of the demonstration, 23 projects were chosen. The data used to evaluate these projects are shown in Table 3. The 23 projects range in cost from $600,000 to $9 million. In this instance, three measures of need are employed, all measured in terms of remaining service life. The first dimension is a distress indicator that reflects for the most part surface cracking. The second measure is the remaining service life of the roadway structure. The third measure of need is the number of years until the PSI falls below an acceptable level. Although in many instances these dimensions are related, they each capture a different aspect of the pavement condition and expected remaining service. Project outcomes are measured in terms of project length and service life added by the project on each of the three dimensions. Finally, traffic loads are included in the model. Thus the DEA pavement model demonstrated here includes the following variables:

1. Project cost, an input;
2. Remaining service life—distress, a nondiscretionary input;
3. Remaining service life—structural condition, a nondiscretionary input;
4. Remaining service life—PSI, a nondiscretionary input;
5. Project length, an output;
6. Added service life—distress, an output;
7. Added service life—structural condition, an output;
8. Added service life—PSI, an output; and
9. Equivalent single-axle loads (ESALs), a nondiscretionary output.

Table 4 provides the results of the DEA evaluation of these projects. The first two columns following the identification

TABLE 3 Pavement Model Demonstration Data

ID	Project Cost	Service Life: Distress	Service Life: Structural	Service Life: PSI	Project Length	Added Life: Distress	Added Life: Structural	Added Life: PSI	ESALs
27	4,326,257	8.933	17	4.800	0	11.067	3	15.200	1,284.2
28	3,974,031	7.560	16	7.200	0	10.440	2	10.800	1,344.2
29	6,300,000	12.400	12.2	8.667	8.7	7.600	7.8	11.333	1,699.7
30	1,000,000	7.500	16	12.900	3.5	10.500	2	5.100	1,269.6
31	3,910,850	5.667	16	16.667	0	19.333	9	8.333	1,269.6
32	1,000,000	4.947	12.2	5.133	5.30	9.053	1.8	8.867	1,150.7
33	1,700,000	0	10.1	0.000	59.1	15.000	4.9	15.000	34.2
34	9,000,000	0	3.7	1.667	17.5	10.000	6.3	8.333	496.8
35	4,000,000	0	11.3	1.500	13.9	15.000	3.7	13.500	81.4
36	4,000,000	11.733	14.7	7.333	4.2	8.267	5.3	12.667	415.8
37	600,000	0	8.3	0	4.6	13.000	4.7	13.000	9.3
38	3,000,000	0.653	9	3.733	21.4	13.347	5	10.267	63.8
39	4,000,000	0.267	2.2	1.667	11.4	9.733	7.8	8.333	434.2
40	3,000,000	7.280	9.4	0	8.5	6.720	4.6	14.000	22.4
41	4,905,772	1.417	10	5.833	4.5	23.583	15	19.167	652.3
45	3,525,000	25.000	17	15.000	1.40	0	8	10.000	134.3
46	3,300,000	10.333	13.3	6.000	1.5	9.667	6.7	14.000	123.3
47	7,000,000	0	8	8.667	3.5	20.000	12	11.333	77.6
48	4,500,000	0	12.3	5.000	1.1	30.000	17.7	25.000	32.6
49	3,200,000	1.300	16.6	2.000	1.20	28.700	13.4	28.000	391.0
50	4,500,000	0	5.8	9.167	4	25.000	19.2	15.833	274.3
51	1,082,061	14.667	10	5.000	1.98	10.333	15	20.000	122.1
52	1,704,933	15.467	14	1.333	0.8	4.533	6	18.667	141.1

(ID) show the results if no assumptions are made regarding the relative importance of each dimension. In this case 15 of the 23 projects are on the productivity frontier.

Once again, the relative importance of project length to improvement must be considered. Clearly project length is a dimension that should be included in the analysis; otherwise the results will be systematically biased against large projects. On the other hand, it seems unlikely that length is as important as improvement. If assumptions are made regarding the relative importance of the dimensions considered, the rankings change quite noticeably. To demonstrate this, the following relationships were assumed to reflect UDOT priorities:

1. All measures of improvement are at least twice as important as project length.
2. Traffic loads carried are more important than project length.
3. Among the nondiscretionary inputs, structural condition is the most important factor, followed by PSI and distress, in that order.
4. Among the nondiscretionary outputs, structural condition is the most important factor, followed by PSI and distress, in that order.

Using these assumptions, the DEA scores were recalculated and the revised scores are shown in Table 4 in the column headed PPS Index, Weighted. A comparison of the two indexes shows that in 11 of 23 cases the project rank was unchanged. In six cases the rank based on the revised score dropped by as much as 21 places. In the remaining six cases the revised rank increased, although the largest increase was five places. These increases in rank were not caused by higher DEA index scores, since adding relative weights can never increase a score. Rather, the ranks for these projects improved because the scores for other projects fell, whereas the scores for these projects were largely unaffected.

For each project not on the frontier, DEA identifies a set of similar but superior projects on the frontier. These comparison sets are identified in the next two columns of Table 4. Each column is headed by the ID for a project that is on the frontier and that appears in one or more comparison sets. The comparison set for each project not on the frontier is indicated with one or more X's in the appropriate columns.

Comprehensive Model

Thus far, the demonstration has involved only projects of a particular type: safety, bridge structures, and similar projects. One of the decisions confronting UDOT, however, involves the comparison of projects designed to address multiple problems, thus providing differing levels of improvement for each major category. What is essentially a pavement project may include safety concerns, capacity enhancements, and bridge improvements. This demonstration involves the overall comparison of the projects in the data base. To make this comparison, all 49 projects are included, and the variables from the four separate demonstrations are used. Thus, the model

TABLE 4 Pavement Demonstration Results

ID	PPS Index					Comparison Groups for Weighted Model							
	No Assumed Weights	Rank	Weighted[a]	Revised Rank	Change in Rank	30	32	34	37	39	49	50	51
27	1.000	1	0.296	16	-15		X		X				
28	0.299	20	0.296	16	+4		X		X				
29	1.000	1	0.379	14	-13		X			X	X		
30	1.000	1	1.000	1	0								
31	0.645	17	0.375	15	+2	X	X		X				
32	1.000	1	1.000	1	0								
33	1.000	1	1.000	1	0								
34	1.000	1	1.000	1	0								
35	1.000	1	0.439	12	-11			X	X			X	
36	0.203	22	0.194	21	+1		X		X				X
37	1.000	1	1.000	1	0								
38	0.326	19	0.202	20	-1	X			X				X
39	1.000	1	1.000	1	0								
40	1.000	1	0.185	22	-21		X		X				X
41	0.971	16	0.971	11	+5		X		X	X	X	X	
45	0.178	23	0.157	23	0	X							X
46	0.221	21	0.213	19	+2		X		X				X
47	1.000	1	0.246	18	-17				X			X	
48	1.000	1	1.000	1	0								
49	1.000	1	1.000	1	0								
50	1.000	1	1.000	1	0								
51	1.000	1	1.000	1	0								
52	0.544	18	0.435	13	+5		X		X				X

a. Improvement is at least twice as important as project length; Traffic load is more important than length; Structural factors are more important than either distress or PSI; PSI is more important than distress

consists of 22 variables: 1 input (cost), 8 nondiscretionary inputs, 10 outputs, and 3 nondiscretionary outputs.

Initially, no assumptions are made regarding the relative importance of each dimension, with the result that roughly half of the projects are on the frontier. Weighted PPS scores are then calculated on the basis of combining the weighting decisions from each submodel. As noted earlier in the discussion of relative weights, some DEA scores in the revised analysis are largely unaffected by the additional information on relative importance. Others are changed markedly. When they occur, the changes are caused by the project attributes and the imposed restrictions on the nature of trade-offs between the factors used in the analysis.

If the arbitrary assumption is made that only projects on the frontier will be constructed, the overall budget for the 21 projects thus selected will be just under $42 million. The construction program will include projects ranging in size from $50,000 to $9 million (the largest evaluated). Of course this is an arbitrary assumption, because budgets generally are not set after examining projects but are more often determined exogenously by a legislature or other funding agency. In actual practice, projects would be ranked on the basis of the DEA score and then would be selected starting at the top of the ranking and moving down until the budget is exhausted.

One of UDOT management's major concerns is the distribution of transportation resources between urban and rural areas. No attempt was made in evaluating these demonstration projects to distinguish between urban and rural projects, except to the extent that traffic loads were included in some models. It is important therefore to consider whether the DEA approach has any inherent bias in favor of either urban or rural areas. Although the majority of projects proposed came from more urban districts, the selection rate within each district varied from 36 to 50 percent and was fairly comparable. The exception came in one district that "submitted" only three projects, none of which were on the frontier. Even so, there does not seem to be any inherent bias toward either urban or rural areas.

Neither is there any inherent bias for or against any particular type of project. Four safety projects were selected, along with six bridge projects and eleven pavement projects. Again, this distribution appears to be comparable to the distribution of projects submitted, although no effort was made to balance the selection. Clearly one of the strengths of the DEA approach is its inherent balancing of factors considered, within the limits of project attributes and imposed weights.

A final aspect of DEA that can be demonstrated here involves the imposition of a requirement that some particular project be carried out, regardless of its DEA evaluation. Suppose for example that for political reasons all districts must have at least one project. As noted above, none of the projects proposed by one district was selected. The case is made that Project 4 in that district should be constructed. Project 4 is the highest-ranking project submitted by the district, and indeed, in the initial bridge analysis it was on the frontier. If Project 4 is selected for construction, Project 11 is the most logical project to drop (assuming constrained budgets and the impossibility of building both). The data clearly demonstrate that the two projects are very similar. Both are bridge replacements funded from state moneys, with no other pavement or capacity implications, although Project 11 does have safety implications not found in Project 4.

The following are the net effect of replacing Project 11 with Project 4.

1. The state will spend an additional $541,000, the difference in the cost of the two projects;
2. The net improvement to bridge deck service life will be shortened by 1.4 years, the difference in the deck improvement resulting from the two projects;
3. The net improvement to bridge substructure service life will be shortened by 2.9 years; and
4. One additional preventable accident will occur every 3 years.

Thus, the DEA analysis enables identification quite specifically of what the trade-offs are in project substitution.

This comparison does not argue against the substitution of two projects. Such a judgment ultimately must be based on the managerial judgment of political leaders and should include factors that can never be successfully incorporated in a mathematical model. What the comparison does indicate is that constructing Project 4 will have costs, and those costs can be identified and specified with the help of DEA in terms of lost opportunities. If the state constructs Project 4, it likely cannot construct Project 11. The cost of constructing Project 4 over Project 11 can be stated in terms of additional dollars, shortened service life, and additional accidents.

One might argue that Project 11 ought not to be dropped. Rather, some other project should be found that could be replaced with Project 4. One implication of such a decision is that those factors promoted in Project 4 (bridges) are more important than the factors enhanced by the other project that will be dropped from the construction program. If this is true, then the comparative importance of the dimensions involved should be made explicit; otherwise there is no assurance that the resulting DEA priorities accurately reflect UDOT managerial priorities. Rendering these judgments explicit is relatively straightforward. It involves adding to the analysis judgments on the relative importance of broad categories. For example, safety may be judged more important than bridges or pavement condition more important than capacity. The analysis reported above would then be rerun to reflect this additional information.

Again, it should be stressed that DEA will not and should not make final allocation decisions. It is fully expected that UDOT personnel will recommend changes in the DEA rankings, and the final decisions must of course pass the scrutiny of political leaders. But to the extent that decision priorities and criteria can be rendered explicit, they can be incorporated in DEA and thus make the processing of information more efficient. The intent is not to replace expert judgment but rather to aid and enhance that judgment.

PROPOSED INTEGRATION OF DEA INTO EXISTING DECISION STRUCTURES

When the conceptual framework articulated above is linked with the DEA methodology, the result is called the project prioritization system or PPS. PPS allows transportation planners and programmers to incorporate into the prioritization process engineering judgment, sound managerial practice, and political values. The purpose of this concluding section is to describe how PPS can benefit transportation decision making by demonstrating how the methodology can be integrated with UDOT policies and procedures.

It is important to note that there are three different components to the PPS proposed here. First, there is the conceptual framework. In this framework, each potential project is characterized in terms of the need for the project, the improvement that will result if the project is carried out, and the costs associated with project implementation. Second, this framework must be implemented within the context of UDOT's existing data collection activities. Although the existing data sources and evaluation methods will clearly evolve over time, current decisions can be based only on currently available data. The conceptual framework articulated here can be used as a guide in the development and evolution of the data collection and evaluation activity, but it is vital that current data and the conceptual framework not be confused. The individual data items articulated in Table 1 will change over time; indeed entirely new measures may be developed as new technologies emerge. This in no way compromises the power or utility of the conceptual framework for evaluating projects.

Finally, the conceptual framework and the available data are combined and analyzed in the PPS software. Taken by itself, the PPS software is simply an implementation of a fairly generic DEA software package. Neither the conceptual framework nor the individual data items have been hard coded into the software. Should the conceptual framework be modified, and when the data items are improved, there will be no need to modify the software. In conducting any analysis, the user must simply indicate how the software should treat each variable included in the assessment.

As powerful as PPS is, no decision of the magnitude of UDOT's highway construction budget should ever be made solely on the basis of a model. PPS should be thoroughly integrated into UDOT decision procedures, and the output from the model should be carefully reviewed at each stage. There are six points or contexts in which PPS can be of significant benefit to UDOT. These may be summarized as follows:

1. The planning staff can use PPS on system-level data to help identify potential problem sites around the state. In this instance, the only variables available will be measures of current (and projected) utilization and the various measures of need. The output of this stage of the analysis would be a ranking of all sites (e.g., corridors, subdistricts) in the state on the basis of need.
2. Given alternative strategies and conditions for the various corridors around the state, PPS can be used to evaluate and rank corridor plans on the basis of greatest need, and the comparative value of specific proposals.

3. In system preservation planning, given a set of conditions at a particular site or along a corridor, and alternative concepts for improving those conditions, PPS can be used to evaluate and select the most effective strategy. In this case, each alternative concept is considered a separate project. All strategies will likely have the same measures of need, since need reflects current conditions. Each alternative strategy will differ in the amount of improvement it provides and the cost of obtaining that improvement. Thus the output of this type of analysis will be a ranking of all strategies based on the relative cost effectiveness of each. This type of analysis could be carried out by either district or central office personnel engaged in preliminary design work. It is recommended that the results of such analyses be compiled, since it seems likely that relatively superior strategies will emerge over repeated evaluations.

4. A similar application of PPS can be used in capacity planning. Here it may prove more difficult to assess project outcomes, since at least some of the outcomes will occur at the system level. Nonetheless, it is vital for UDOT to estimate such outcomes, whether or not the PPS system is used to evaluate alternative strategies.

5. Given the outputs from the planning activities within each major category (e.g., roadway management, safety, structures), PPS can be valuable in providing an overall assessment and comparison of proposed projects. This assessment can then be combined with public input, funding estimates, and other subjective information to yield the projects that will continue to the next phase of scoping or preliminary engineering.

6. Finally, once need, improvement, and project cost data have been refined, PPS can be used again to evaluate and rank projects before finalizing the transportation improvement program.

It is anticipated that after review, division heads and district directors may wish to modify a priority listing generated by the PPS. The proposed procedure permits such a modification, but it is strongly recommended that the change be justified in some way. Further, the review process should require that consideration be given to which projects will be eliminated if the change in priorities is made. The change may in fact take place, but the costs will, under this proposal, be identified explicitly and considered in the decision to change a priority. Note that at no stage does PPS replace qualified engineering and managerial judgment. Rather, it provides another tool to evaluate complex and often conflicting sets of data and it can provide guidance in considering the inevitable trade-offs involved in managing a contemporary highway system.

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