Decision Analysis of Alternative Highway Alignments

By Ram B. Kulkarni,[1] Robert L. Burns,[2] John Wright,[3] Bryan Apper,[4]
Thomas O. Baily,[5] and Stephen T. Noack[6]

(Reviewed by the Highway Division)

Abstract: The evaluation of alternative alignments for a proposed highway project in California required taking into account impacts on a variety of environmental and socioeconomic issues. Techniques of formal decision analysis were used to evaluate the overall impact of each alternative alignment and to rank the alignments in an ascending order of the overall impact. A multiattribute penalty function was calibrated using acceptable trade-offs among impacts on different issues as assessed by a project team of scientists and planners. Results of decision analysis suggested that one of the alternative alignments should be most preferred under a variety of assumptions and value judgments. This alternative was recommended for further analysis and inclusion in a draft environmental impact report/statement. The application of decision analysis to this evaluation problem was effective because it: (1) Provided a rational procedure to address multiple and often conflicting environmental and socioeconomic issues; (2) facilitated sensitivity analysis to evaluate the impact of perceived value judgments of different concerned groups on the ranking of the alternatives; and (3) provided a full documentation of the evaluation process.

Introduction

This paper describes the application of formal decision analysis to evaluate alternative alignments for a proposed highway project. The specific project for this evaluation was a portion of the California State Highway Route 180 east of the City of Fresno between Fowler Avenue and Cove Avenue. The California Department of Transportation (Caltrans) has proposed to increase the capacity of Route 180 within the project limits so that traffic operates at least at level of service (LOS) C. At present the roadway has a substandard horizontal and vertical alignment, insufficient lane and shoulder widths, and sight distance restrictions at several locations. The proposed improvements will be designed to alleviate these deficiencies.

Six alternative alignments were identified as being feasible based on a preliminary engineering analysis. Each of these alternatives can be designed

[1]Vice Pres. & Prin., Woodward-Clyde Consultants, 500 12th Street, Suite 100, Oakland, CA 94607-4014.

[2]Vice Pres., Centennial Civ. Engrs., Inc., 5000 Hopyard Rd., Suite 100, Pleasanton, CA 94588.

[3]Headquarters Hydr. Engr., Office of Project Planning and Development, California Dept. of Transp., 650 Howe Ave., Suite 400, Sacramento, CA 95825.

[4]Chief, Envir. Oversight, Branch B, California Dept. of Transp., District 6, 4545 N. West Ave., Fresno, CA 93705.

[5]Dir., Envir. Mgmt. Div., Woodward-Clyde Consultants, 500 12th Street, Suite 100, Oakland, CA.

[6]Sr. Business Development Mgr., Woodward-Clyde Consultants, 500 12th Street, Suite 100, Oakland, CA.

Note. Discussion open until October 1, 1993. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on October 30, 1991. This paper is part of the ***Journal of Transportation Engineering***, Vol. 119, No. 3, May/June, 1993. ©ASCE, ISSN 0733-947X/93/0003-0317/$1.00 + $.15 per page. Paper No. 2888.

J. Transp. Eng. 1993.119:317-332.

to achieve the desired LOS. However, the environmental and socioeconomic impacts of the alternatives vary substantially. Furthermore, no single alternative is more desirable than all remaining alternatives with regard to each of the potential impacts. That is, an alternative may have a lower (adverse) impact on one particular factor, but a higher impact on some other factor. A proper evaluation of the alternatives, therefore, requires an assessment of acceptable trade-offs between various impacts. Such trade-offs obviously depend on subjective value judgments and may vary from one individual to another. A logical and rational method to evaluate the alternatives is required to assure that the basis of the evaluation is defensible and can be fully documented.

A formal decision analysis incorporating a multiattribute value model was used to meet these objectives. The model provides the ability to properly balance multiple and often conflicting issues relevant to the evaluation of alternative alignments. This balancing of issues utilizes the technical consensus and value judgments of a group of scientists, engineers, and administrators. The model facilitates performing sensitivity analyses to evaluate the impact of using different value judgments defined to represent the perspectives of various concerned groups. The objective of these analyses is to identify one or more preferred alternatives that are consistently ranked near the top under a variety of value judgments. Such alternatives are more likely to receive the support of many of the diverse concerned groups, thus improving the likelihood of public acceptance of the project.

This paper is organized as follows. The next section describes the background of the proposed project and identifies the six feasible alternative alignments. The following sections provide an overview of the decision analysis method and describe the main steps in implementing the model. The final section discusses the usefulness and limitations of the decision analysis method for this type of evaluation problem.

Project Background and Description of Alternative Alignments

Route 180 is a principal arterial that runs roughly east-west across the northern half of Fresno County, serving traffic between the west side of the San Joaquin Valley and Sequoia and Kings Canyon national parks. The portion of Route 180 addressed by this project is east of the City of Fresno between Fowler Avenue and Cove Avenue [post mile (PM) 67.6 and 83.8].

The project route represents one of the major routes for recreational traffic to Kings Canyon and Sequoia national parks. The route also serves agricultural goods transport from the vineyards and orchards east of Fresno, and is of growing importance for commuter travel between the Fresno-Clovis Metropolitan Area (FCMA) and eastern Fresno County.

The purpose of the proposed project is to increase the capacity of Route 180 within the project limits so that traffic operates at least at LOS C. This will decrease traffic delays and accidents on the project route. At present the roadway has a substandard horizontal and vertical alignment, insufficient lane and shoulder widths, and sight distance restrictions at several locations. These deficiencies have resulted in a current LOS ranging from D to E, and along most of the project route, accident rates are nearly twice the statewide average. Based on future traffic projections, vehicle operating conditions on the project route will become much worse over the next 20 years without highway improvements.

Six alternative alignments were analyzed to improve the Rural Route 180 from Fowler Avenue to Cove Avenue. These alternative alignments were identified by Caltrans based on preliminary engineering and environmental evaluations, and included alignments requested by the Sanger Chamber of Commerce and the Fresno County Board of Supervisors. Fig. 1 shows the six alternative alignments within the corridor.

Alternative 1 follows the existing Route 180 alignment, and has three variations that are labeled with reference to the way the existing highway is used in the new facility. Alternative 1N uses the existing highway as a frontage road north of the proposed mainline, Alternative 1M incorporates the existing highway as one of the mainlines in the freeway or expressway, and Alternative 1S utilizes the existing highway as a frontage road south of the proposed mainline.

There are significant differences in the environmental and socioeconomic impacts of the six alternatives. For example, alternative 1, along with alternative 3, follows the existing alignment through the town of Centreville. This requires a considerable amount of building relocation as well as construction disturbance to residents of Centreville. Estimates of specific impacts of each alternative are discussed in a following section.

Overview of Decision Analysis Method

Decision analysis is a systematic and logical procedure based on a set of axioms for rationally analyzing decision problems. This method is particularly effective for decision problems involving multiple and often conflicting objectives (Keeney and Raiffa 1976). Techniques of decision analysis allows for separately assessing technical and value judgments, and then combining these judgments in a consistent manner to provide rational criteria for ranking alternatives. Technical judgments are needed to estimate the impact of

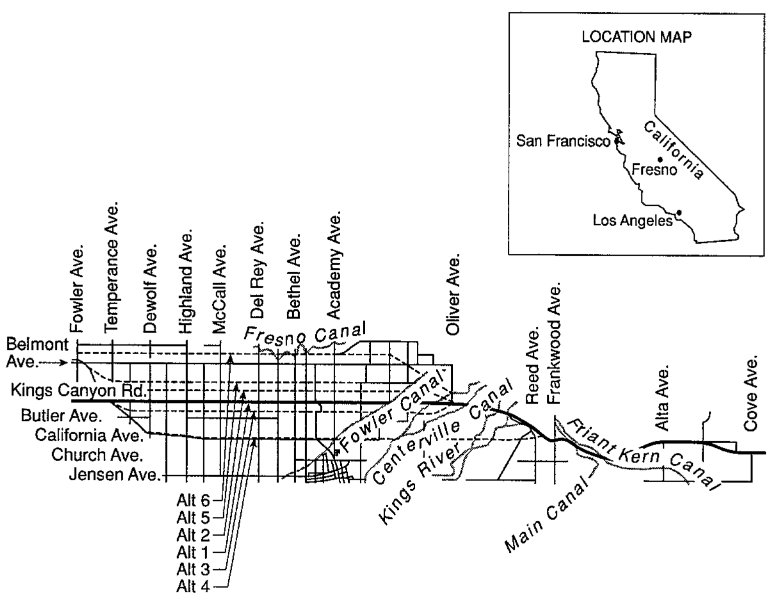

FIG. 1. Alternative Highway Alignments

an alternative on the relevant objectives. Value judgments are needed to assess the decision maker's preferences for different impacts.

To describe the process of evaluating alternatives using decision analysis, let X_i, $i = 1$ to n, denote a set of attributes that measure the impact on relevant objectives, and let x_i denote a specific level of the attribute X_i for a given alternative. Thus, the vector $\mathbf{x} = (x_1, x_2, \ldots, x_n)$ characterizes the levels of all attributes for a given alternative. A key component of decision analysis is a model of the decision maker's preferences (values). Let $v(\mathbf{x})$ denote such a model; specifically $v(\mathbf{x})$ is a penalty function that can be used to calculate the overall penalty (or undesirability) of the attribute vector $\mathbf{x}$ associated with a given alternative. For mathematical convenience, this function is scaled from 0 to 1, with higher numbers indicating a greater penalty. Under certain assumptions (which were found to be valid for this project), the function $v(\mathbf{x})$ can be expressed as follows (Dyer and Sarin 1979):

$$v(\mathbf{x}) = \sum_{i=1}^{n} k_i v_i(x_i), \qquad (1)$$

where $v_i(x_i)$ = penalty function for the attribute X_i, scaled from 0 to 1; k_i = scaling constants, in the range of 0 to 1; and $\Sigma\, k_i = 1$.

The single-attribute penalty functions, $v_i(x_i)$ are defined by assessing the relative penalties of different levels of the given attribute X_i. Note that any nonlinearity in the penalty function is captured in assessing the relative penalties. For example, a specified increase in a given attribute may be viewed to be more critical at lower levels of the attribute.

Each scaling constant weights the contribution of the corresponding attribute to the overall penalty. However, it is not strictly correct to interpret the scaling constants as the relative weights of the different attributes. This is because the magnitude of a scaling constant depends not only on the relative importance of the corresponding attribute, but also on the range of the attribute among the alternatives. Consider, for example, the situation in which a particular attribute is judged to be very important, but the attribute does not vary much among all alternatives. In this case, the scaling constant for the attribute would be relatively small. In contrast, the scaling constant would be larger if the range of the attribute among the alternatives is greater.

The scaling constants, k_i are calculated by assessing value trade-offs between different attributes. The value trade-offs indicate how much the decision maker would be willing to give up on one attribute in order to achieve a specified improvement on another.

The overall penalty function, $v(\mathbf{x})$ is fully calibrated once the individual penalty functions, $v_i(x_i)$ and the scaling constants, k_i are defined. To evaluate alternatives, the attribute levels of each alternative are estimated and the overall penalty of the alternative is calculated using (1). All the alternatives are then ranked in a descending order of the overall penalty.

Certain limitations of this decision analysis model should be noted. First, the model assumes that attribute levels of each alternative are known with certainty. In real life, the attribute levels are estimated from available data. These estimates may entail substantial uncertainty. For this project, the estimation uncertainty was judged to be relatively small, because detailed spatial data were available for the alternative alignments. If, in fact, the estimation uncertainty is large, the use of utility functions that incorporate the concept of risk would be more appropriate (Keeney and Raiffa 1976).

Second, if the attributes used to evaluate alternatives have preferential dependencies (i.e., the penalty for a given attribute depends on the level of that attribute plus the levels of some other attributes), the form of the penalty function can become much more complex than the additive form shown in (1). The assessment of a complex penalty function is difficult and often impractical. In practice, however, the assumption of preferential independence is usually reasonable, particularly if the attributes are defined carefully to avoid any overlap.

Finally, the analysis requires an explicit assessment of acceptable trade-offs among conflicting objectives. In some cases, decision makers may not be willing to make public statements of such acceptable trade-offs.

IMPLEMENTATION OF DECISION ANALYSIS METHOD

The implementation of the decision analysis method for this project involved the following steps:

1. Structure the decision problem.
2. Assess preferences (values) of decision makers.
3. Estimate possible impacts of each alternative.
4. Evaluate and compare alternatives.

Each of these steps is described in the following sections.

Step 1. Structure Decision Problem

Structuring the decision problem required the following tasks:

- Selecting the alternatives that are to be evaluated
- Identifying the major impact factors that need to be addressed in the evaluation process
- Defining attributes that measure the impacts on the various issues
- Identifying the individuals whose technical and value judgments will be used to evaluate the alternatives

The completion of these tasks is described as follows.

Selecting Alternatives

The alternative highway alignments included in this evaluation were identified in the previous section.

Identifying Major Impact Factors

The main objective of the evaluation process was to support the preparation of a draft environmental impact report/statement. Therefore, the major impacts relevant to this evaluation were environmental and socioeconomic. Construction costs of alternative alignments were not considered in the evaluation, because the National Environmental Protection Act (NEPA) and the California Environmental Quality Act (CEQA) required that alternatives be evaluated without the consideration of construction costs. The following impact factors were identified as being relevant to the evaluation of the alternatives:

- Land use

J. Transp. Eng. 1993.119:317-332.

- Relocation
- Agricultural production
- Biological resources
- Cultural resources
- Air quality
- Noise

Defining Attributes

For each of these factors, one or more attributes were identified that measure the level of impact (see Table 1). The definition of each of the attributes is provided in the following.

- Number of parcels split—If a particular alignment passes through an existing parcel, the parcel would be split, thus impacting its operation and use. The degree of impact of a split parcel can be assessed by defining the following categories (in a descending order of impact):
  - Alignment splits the parcel so that one or more of the remnants become economically inviable for existing land uses that have been zoned for the area. Economic viability is defined as a minimum of 40,470 m^2 (10 acres) of prime farmland or 161,880 m^2 (40 acres) of nonprime farmland.
  - Alignment splits the parcel so that one or more of the remnants is economically inviable for the current landowner; however, if the remnant(s) is combined with an adjacent parcel, it will remain economically viable for the existing land uses that have been zoned for the area.
  - Alignment splits the parcel so that all of the remnants remain economically viable to the current landowner.
- Number of buildings displaced—This attribute addresses the socioeconomic impact of relocation on families and businesses. Three

TABLE 1. Issues and Attributes for Evaluating Alternative Alignments

Issue in evaluating alternative alignments (1)	Evaluation attributes (2)
Land use	number of parcels split
Relocation impact	number of buildings displaced
Agricultural production	acreage of prime farmland taken out of production
	acreage of Williamson Act land taken out of production
Biological resources	acreage of riparian wetlands affected
	number of valley oaks removed
	number of elderberry plants removed
Cultural resources	number of properties of potential historic importance affected
Air quality	percentage difference in vehicle-miles between alternatives
Noise	number of residences affected by noise

J. Transp. Eng. 1993.119:317-332.

categories of buildings were defined. These categories, in a descending order of impact, are:

- Number of farm complexes displaced—A farm complex includes a residential building as well as farming facilities.
- Number of businesses displaced—Examples of such businesses are gas stations and grocery stores. Typically, multiple structures will be involved for each business site.
- Number of homes displaced—These would be typically single structures used primarily for residence.

- Acreage of prime farmland taken out of production—Prime farmland is defined as class I and class II soils mapped by the U.S. Soil Conservation Service. Any unique or statewide important farmland taken out of production is also included in this attribute.
- Acreage of Williamson Act land taken out of production—This attribute reflects the concern that if the highway construction requires the acquisition of land protected by the Williamson Act, the permitting of such an alignment may require considerable documentation to show that any socioeconomic impact would be minimal and can be mitigated. The Williamson Act is intended to provide a monetary incentive to keep land in agricultural production by providing a lower assessed value for land under the Williamson Act contract. Land can only be removed from contract by approval of the local county or by stated intention of the landowner with an extended waiting period.
- Acreage of riparian wetlands affected—This attribute addresses the impact of an alignment on riparian wetlands and their habitats.
- Number of valley oaks removed—Valley oaks are an important environmental resource. This attribute defines the number of valley oaks removed because of a given alignment.
- Number of elderberry plants affected—Elderberry plants are habitats of valley elderberry longhorn beetles. This attribute addresses the impact on this habitat.
- Number of properties of potential historic importance affected—This attribute is defined in terms of the number of properties potentially eligible for the National Register of Historic Places that would be directly damaged by highway construction, or construction on the alignment would have a significant indirect impact on the property. A significant indirect impact may result from: (1) An alteration of the character of the setting where the setting contributes to the quality of structures on the property; or (2) an introduction of inappropriate visual, audible, or atmospheric elements to the setting. Potentially eligible properties for this attribute include those containing structures that have been identified for their historic value by the state or local jurisdictions, structures that are at least 50 years old, and structures that have been identified as having potential significant historic architectural value.
- Percentage difference in vehicle-kilometers—For a projected volume of traffic, the alternative alignments may involve different lengths of travel both off-route (to get on the highway) and on-route. The greater the length of travel, the higher would be the number of vehicle-miles traveled. This attribute was estimated by converting

the difference between the shortest alternative and the other alternatives into percentages. For example, alternative 3 was the shortest route so it would represent 0, while alternative 6 was the longest route at 2.81% longer than alternative 3. This attribute reflects concerns about environmental impacts (air pollution) and socioeconomic impacts (vehicle operating costs) resulting from an increase in the number of vehicle-kilometers traveled. The number of vehicle-kilometers for alternative 3 was estimated.

- Number of residences affected by noise—This attribute is defined in terms of the number of residences that are within a certain distance from the highway so that the estimated noise level within this distance zone would be above an acceptable threshold.

Identifying Individuals for Assessing Technical and Value Judgments

Technical judgments were needed to estimate the impacts of each alternative alignment in terms of the attributes defined. Scientists and engineers with background in the appropriate disciplines estimated these impacts.

Value judgments were needed to assess trade-offs between different attributes. For this purpose, we assembled a group of selected individuals from the consultant's project team, who had expertise in the relevant environmental and engineering issues, and appropriate Caltrans personnel who have the responsibility of making recommendations regarding the selection of an alignment. Consensus value judgments of this group were used to develop a value model as described in the next section.

Step 2. Assess Preferences (Values) of Decision Makers

The following assessments were needed to develop the overall penalty function used to evaluate the alternative alignments:

- Range of impact levels of each attribute
- Equivalency factors of different categories of a given attribute
- Penalty functions for individual attributes
- Value trade-offs between different attributes

Our approach was to obtain a group consensus, through discussion and sharing of experience and information, on each of the assessments made. Where significant differences of opinions remained even after group discussions, we identified alternative assessments that were used in conducting sensitivity analysis. Results of the various assessments are described in the following.

Range of Impact Levels of Each Attribute

Table 2 shows the lowest and the highest estimated impact levels of each attribute for the set of alternative alignments identified previously.

Equivalency Factors for Different Categories of Given Attribute

As discussed in the previous section, multiple impact categories were defined for each of the following two attributes: number of parcels split and number of buildings displaced. The categories for each attribute were first ranked in a descending order of the associated impact. One unit of the highest impact category was then equated to different numbers of units for other impact levels. For example, the group assessed that the impact of one

J. Transp. Eng. 1993.119:317-332.

TABLE 2. Range of Impact Levels for Each of Attributes

Attribute (1)	Lowest impact level (2)	Highest impact level (3)
Equivalent number of parcels split in category A	20	100
Equivalent number of buildings displaced in category A	4	80
Acreage of prime farmland taken out of production	100	350
Acreage of Williamson Act land taken out of production	50	250
Acreage of riparian wetlands affected	10	30
Number of valley oaks removed	10	50
Number of elderberry plants removed	0	5
Number of properties of potential historic importance affected	0	25
Percentage difference in vehicle-miles travelled	0	3
Number of residences affected by noise	20	150

remnant parcel in category A was equivalent to the impact of two remnant parcels in category B and eight remnant parcels in category C. These equivalency factors provided the means to convert the estimated impact levels for different categories into an equivalent impact level in the category with the highest impact level. For the example of split parcels, x remnant parcels in category B would be converted into $x/2$ equivalent remnant parcels in category A, and y remnant parcels in category C would be converted into $y/8$ equivalent remnant parcels in category A. All of these equivalent numbers of remnant parcels in categories B and C would be added to the number of remnant parcels in category A to obtain the total equivalent number of remnant parcels in category A.

For the second attribute, namely, the number of buildings displaced, the group agreed that a farm complex displaced would have the highest impact. However, there was some disagreement regarding the equivalency factors for the other two categories. We identified a base case and a sensitivity analysis case to address these differences in value judgments. For the base case, the equivalency factors for the three categories, A, B, and C, were 1, 0.5, and 0.5, respectively. For the sensitivity analysis case, the equivalency factors for the three categories, A, B, and C, were 1, 0.33, and 0.25, respectively. The reason for this difference of opinion was that some individuals believed that relocating a business would be much harder than relocating a home, thus causing a greater socioeconomic impact, while others believed that the socioeconomic impact of displacing a business or a home would be about the same.

Penalty Functions for Individual Attributes

A penalty function, $v_i(x_i)$ for the attribute X_i provides an assessment of the relative degree of concern regarding different impact levels of the attribute. The range of impact levels of each attribute, assessed earlier, calibrated the end points of the penalty function for that attribute. Impact values of 1 and 0 were assigned to the highest and the lowest impact levels of each attribute, respectively. It was explained to the group of assessors that if the degree of concern for each unit of attribute (e.g., each building) was the same, this implied a linear function for $v_i(x_i)$. If, on the other hand, the incremental impact of each additional unit is different, a nonlinear function would be appropriate. For example, if the first few units cause most of the impact, this would imply a nonlinear function. After group discussions, nonlinear penalty functions were assessed to be appropriate for two of the attributes, namely, acreage of riparian wetlands affected and the number of elderberry plants removed. Linear penalty functions were assessed to be appropriate for all of the remaining attributes.

For the nonlinear penalty functions, the group was asked to assess the cumulative impact of an increasing number of units of an attribute. Consider, for example, the square meters of riparian wetlands affected. This attribute has the range of 40,470–121,410 m^2 (10–30 acres). Thus, the end points of the penalty function for this attribute are calibrated as follows: impact penalty of 0 for 40,470 m^2 (10 acres) of wetlands (note that this is a relative penalty for the lowest level of impact among the alternatives) and penalty of 1 for 121,410 m^2 (30 acres) of wetlands. The assessment of the group was that 50% of the total impact would occur if 72,846 m^2 (18 acres) of wetlands are affected, thus providing a penalty of 0.5 for the impact level of 72,846 m^2 (18 acres) of wetlands affected. A similar assessment for the number of elderberry plants removed resulted in a penalty of 0.5 for the impact level of two elderberry plants removed. Using the two defined end points and the assessed midvalue point, individual penalty functions were defined for the two attributes discussed previously. These functions are shown on Fig. 2. As noted previously, the individual penalty functions for all other attributes were linear.

Value Trade-Offs between Different Attributes

A value trade-off was assessed between each of the attributes in Table 1 and dollars. Specifically, the trade-off question was formulated as: How much money would you be willing to pay in order to avoid the incremental impact between the lowest and highest impact levels of a given attribute?

It was explained that the trade-off question did not ask for an estimate of the cost needed to mitigate the impact from its highest to the lowest level. Although the magnitude of the mitigation cost would be one factor in addressing the trade-off question, it might not be the only factor. A decision maker may be willing to pay more than the cost of mitigation in order to avoid the incremental impact altogether. Avoidance of an impact would not only make mitigation unnecessary, but would also preserve the existing environmental values and resources or avoid socioeconomic impacts on families and businesses.

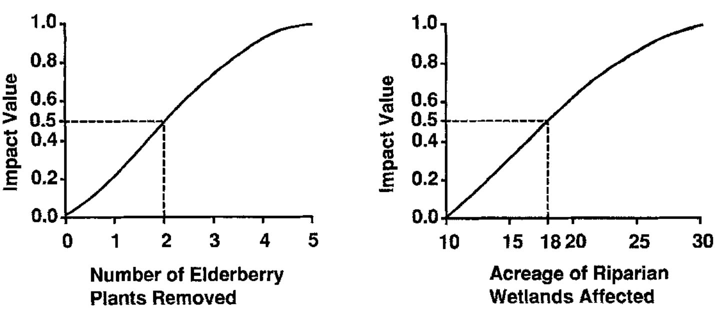

FIG. 2. Nonlinear Penalty Functions

Table 3 shows the amount of money the group would be willing to pay to avoid the incremental impact on each of the attributes. The incremental impact for each attribute was defined to be the difference between the lowest and highest impact levels of the attribute shown in Table 2. This difference was generally larger than the actual range of attribute levels for the seven alternatives shown in Table 4. The reason for this was to define a penalty

TABLE 3. Value Trade-Offs for Different Attributes

Attribute (1)	Incremental impact (2)	Amount of money willing to pay to avoid the incremental impact (dollars) (3)
Equivalent number of parcels split in category A	20–100	7,000,000
Equivalent number of buildings displaced in category A	4–80	11,600,000
Acreage of prime farmland taken out of production	100–350	7,600,000
Acreage of Williamson Act land taken out of production	50–250	500,000
Acreage of riparian wetlands affected	10–30	4,000,000
Number of valley oaks removed	10–50	1,000,000
Number of elderberry plants removed	0–5	50,000
Number of properties of potential historical importance affected	0–25	2,500,000
Percentage difference in vehicle-miles traveled	0–3	7,500,000
Number of residences affected by noise	20–150	2,000,000

TABLE 4. Matrix of Impact Levels

Attribute (1)	Estimated Impact Level for Given Alternative						
	1M (2)	1S (3)	1N (4)	2 (5)	3 (6)	5 (7)	6 (8)
Equivalent number of parcels split in category A	49	49	38	36	44	49	52
Equivalent number of buildings displaced in category A	67	60	58	24	27	33	32
Acreage of prime farmland taken out of production	267.6	267.7	267.7	252.5	229.9	298.1	241.7
Acreage of Williamson Act land taken out of production	84.0	84.0	84.0	127.6	69.4	151.9	81.4
Acreage of riparian wetlands affected	16.1	14.5	14.5	13.3	14.5	13.3	13.3
Number of valley oaks removed	23	23	23	15	23	15	15
Number of elderberry plants removed	5	5	5	0	5	0	0
Number of properties of potential historical importance affected	16	16	16	6	21	6	5
Percentage difference in vehicle-miles traveled	0.11	0.11	0.11	0.60	0	1.35	2.81
Number of residences affected by noise	79	79	79	48	57	78	101

function that would be valid even if the attribute levels changed somewhat because of: (1) Possible modifications to some of the alignments; (2) additional field data; and (3) changes in the equivalency factors for different categories of a given attribute for purposes of sensitivity analyses.

To provide a basis for assessing the amount of money one would be willing to pay to avoid the incremental impact on a given attribute, economic consequences of the impact and the cost of an appropriate mitigation program were estimated. Consider, for example, the impact on wetlands. Environmental scientists who had the experience of restoring wetlands were interviewed. The Corps of Engineers requires establishing 12,141 m^2 (3 acres) of new wetlands for each 4,047 m^2 (1 acre) of existing wetlands lost. Thus, the cost of mitigating the impact on 4,047 m^2 (1 acre) of wetlands was estimated as follows: \$15,000 for 12,141 m^2 (3 acres) of replacement land, \$30,000 for habitat replacement, and \$5,000 as a contribution to a state wetlands endowment trust, or a total of \$50,000 per 4,047 m^2 (1 acre) of wetland impact. However, the group of assessors believed that the value of avoiding this impact altogether was much greater than simply the mitigation cost that would be avoided. This was because of the intrinsic value in preserving existing environmental resources and also enhancing the public and regulatory support. The group believed that the intrinsic value was two to four times the cost of mitigation estimated at \$50,000 per 4,047 m^2 (1 acre). For the base case analysis, we assumed a factor of four, i.e., a value of \$200,000 per 4,047 m^2 (1 acre) of wetland impact avoided. Thus, the amount of money one would be willing to pay to avoid the impact on 80,940 m^2 (20 acres) was estimated as \$200,000 $\times$ 20 = \$4 million and is shown in Table 3. For a sensitivity analysis case, discussed later, a value of \$100,000 per 4,047 m^2 (1 acre) of wetland impact avoided was assumed to reflect the lower end of the group's value trade-off.

Consider, next, the percent difference in vehicle-kilometers. Each percent difference in vehicle-kilometers was estimated to be about 966,000 vehicle-kilometers per year. Assuming a project life of 20 years, the maximum 3% difference in vehicle-kilometers amounted to about 57,960,000 vehicle-kilometers (36,000,000 vehicle-miles). The vehicle operating cost was assumed to be \$0.13 per km (\$0.21 per mile). Thus, the maximum difference in vehicle operation cost was estimated to be about \$7,500,000. The group's assessment was that one would be willing to pay up to \$7,500,000 in order to avoid the 3% increase in vehicle-kilometers. However, another opinion was also expressed that a benefit/cost ratio of about 1.5 should be applied to the potential savings of \$7,500,000 in vehicle operating costs. That is, one should be willing to pay up to \$ (7.5/1.5=) 5,000,000 to realize the savings of \$7,500,000 in vehicle operating cost. This variation in the value trade-off was considered in the sensitivity analysis.

A similar process was used to assess other value trade-offs shown in Table 3. Sensitivity analysis cases were defined to address any significant differences of opinions regarding the value trade-offs.

Several consistency checks were applied to the assessment of the value trade-offs. The monetary trade-offs shown in Table 3 were expressed in terms of the implied trade-offs between various attributes, and the reasonableness of these implied trade-offs was examined. For example, consider the trade-off between the attributes of number of parcels split in category A and the acreage of wetlands affected. The monetary trade-offs shown in Table 3 for these two attributes imply that the impact of one acre of wetlands affected would be equivalent to the impact of about two parcels split in category A. The group discussed this implication and found it to be consistent with its judgment regarding an acceptable trade-off between the two attributes.

As the implications of monetary trade-offs were discussed in terms of the implied trade-offs between different attributes, several of the initial monetary trade-offs were judged to be inconsistent. These trade-offs were then revised appropriately.

The scaling constants, k_i, (which reflect the relative weight of attribute x_i appropriate for its range) were calculated as follows:

$$k_i = \frac{m_i}{\sum m_i} \qquad (2)$$

where m_i = the amount of money the decision maker would be willing to pay to avoid incremental impact on attribute X_i. The term $\Sigma\ m_i$ was used in the denominator in (2) so that the scaling constants sum to 1.0. The scaling constants are shown in Table 5 in parentheses.

Step 3. Estimate Impact of Each Alternative

The project team of scientists and engineers estimated the impact level of each attribute for each of the alternatives. Available maps and aerial photographs were used in estimating the various impacts. Table 4 shows the estimated impact levels for each of the alternatives.

Step 4. Evaluate and Compare Alternatives

Table 5 shows the ranking of the alternative alignments in an ascending order of the total weighted penalty [v in (1)]. Also shown in this table are the weighted penalties of individual attributes [$k_i v_i(x_i)$ in (1)]. The total weighted penalty is the sum of the weighted penalties of individual attributes.

The results in Table 5 suggest that alternatives 2 and 3 should be considered more desirable than the remaining alternatives.

Several sensitivity analyses were conducted to evaluate the effects of varying key parameters on the ranking of the alternatives. These analyses consisted of the following:

- Different equivalency factors for the categories of the number of buildings displaced—As noted in Step 2, there was a difference of opinion regarding the equivalency factors of the three categories (A, B, and C) of the number of buildings displaced. For the base case results (shown in Table 5), the equivalency factors of category A, B, and C were 1, 0.5, and 0.5, respectively. For this sensitivity analysis case, the equivalency factors of 1, 0.33, and 0.25 were used for category A, B, and C, respectively. Alternatives 2 and 3 were again the most preferred alternatives.
- Amount of money willing to pay to reduce percentage difference in vehicle-kilometers traveled—As described previously, the amount of money one should be willing to pay to reduce the percent difference in vehicle-kilometers from 3 to 0 was decreased from \$7,500,000 to \$5,000,000 for this sensitivity analysis case. The most preferred alternatives remained the same, namely, alternatives 2 and 3.
- Amount of money willing to pay to reduce impact on wetlands—

TABLE 5. Base Case Results Ranking of Alternative Highway Alignments Run: Base Case

Rank (1)	Site (2)	Split parcels (0.160) (3)	Buildings displaced (0.265) (4)	Acreage of prime land affected (0.174) (5)	Acreage of wetlands affected (0.091) (6)	Valley oaks remove (0.023) (7)	Elderberry plants affected (0.001) (8)	Potential historic properties affected (0.057) (9)	% Difference in vehicle miles (0.171) (10)	Residences affected by noise (0.046) (11)	Williamson land out (0.011) (12)	Total weighted impact (13)
1	alternative 2	0.0320	0.0698	0.1060	0.0341	0.0029	0.0000	0.0137	0.0343	0.0098	0.0044	0.3069
2	alternative 3	0.0480	0.0802	0.0903	0.0362	0.0074	0.0011	0.0480	0.0000	0.0130	0.0011	0.3254
3	alternative 1N	0.0360	0.1866	0.1165	0.0275	0.0074	0.0011	0.0366	0.0063	0.0207	0.0019	0.4408
4	alternative 5	0.0580	0.0994	0.1377	0.0433	0.0029	0.0000	0.0137	0.0771	0.0204	0.0058	0.4583
5	alternative 1S	0.0580	0.1936	0.1165	0.0275	0.0074	0.0011	0.0366	0.0063	0.0207	0.0019	0.4698
6	alternative 6	0.0640	0.0977	0.0985	0.0319	0.0029	0.0000	0.0114	0.1606	0.0285	0.0018	0.4972
7	alternative 1M	0.0580	0.2198	0.1165	0.0363	0.0074	0.0011	0.0366	0.0063	0.0207	0.0019	0.5047

This sensitivity analysis case reflected the opinion that the value of avoiding impact on 4,047 m^2 (1 acre) of wetlands should be considered to be $100,000 (instead of $200,000). The amount of money one would be willing to pay to avoid the incremental impact on wetlands was reduced from $4,000,000 to $2,000,000. Alternatives 2 and 3 were still the most preferred alternatives.

Identification of Preferred Alternatives

Alternatives 2 and 3 are the two top-ranked alternatives under a variety of plausible scenarios. The overall desirability of these two alternatives is substantially greater than that of the remaining alternatives. Between these top-ranked alternatives, the overall desirability of alternative 2 appears to be slightly higher than that of alternative 3.

Based on the results of the evaluation process in this study, alternative 2 was recommended for further analysis and inclusion in a draft environmental impact report/statement (EIR/EIS). Following the NEPA and CEQA requirements, the no-build alternative must also be included in the EIR/EIS. The EIR/EIS will be circulated for regulatory and public review and input. The final decision on the project will be made after taking into account the review comments of the concerned parties.

Summary and Conclusions

Procedures of formal decision analysis were used to evaluate alternative alignments for a proposed highway project. The environmental and socioeconomic issues relevant to this evaluation included: land use, relocation of homes and businesses, agricultural production, biological resources, cultural resources, and air quality. For each of these issues, one or more attributes were identified that measured the impact of a given alignment on the issue. A multiattribute penalty function was developed to evaluate the overall impact of each alternative alignment and to rank the alignments on an ascending order of the overall impact. The penalty function was calibrated using acceptable trade-offs between various attributes as assessed by a project team of scientists and planners. Results of decision analysis suggested that one of the alternative alignments should be preferred to all others under a wide variety of assumptions and value judgments. This alternative was recommended for further analysis and inclusion in a draft environmental impact report/statement.

Decision analysis was particularly effective for this evaluation process because it:

- Provided a rational procedure to address multiple and often conflicting environmental and socioeconomic issues that were relevant to the evaluation of the alternatives.
- Allowed for separately assessing technical and value judgments and then combined these judgments in a consistent manner to provide a rational criterion for ranking alternatives.
- Provided a systematic procedure to represent the anticipated viewpoints and value judgments of different concerned groups and to evaluate the sensitivity of the ranking of alternatives to these representations.
- Provided a full documentation of the evaluation process including

an explicit identification of technical and value judgments used to rank the alternatives.

Decision analysis does require an explicit assessment of acceptable trade-offs among competing objectives. In some cases, decision makers may not be willing to make public statements of such acceptable trade-offs, thus constraining the use of decision analysis. One should keep in mind, however, that the basis of how one arrived at a decision needs to be fully explained for projects subject to the scrutiny of others. Decision analysis facilitates this process.

Appendix I. References

Dyer, J. S., and Sarin, R. K. (1970). "Measurable multiattribute value functions." *Oper. Res.*, 27, 810–822.

Keeney, R., and Raiffa, H. (1976). *Decisions with multiple objectives: Preferences and value tradeoffs*. John Wiley and Sons, New York, N.Y.

Appendix II. Notation

The following symbols are used in this paper:

i = (subscript) index of attribute;
k_i = scaling constant for X_i;
m_i = dollar trade-off for X_i;
$v(\mathbf{x})$ = overall penalty function;
$v_i(x_i)$ = penalty function of x_i;
X_i = ith attribute of impact;
$\mathbf{x}$ = vector of attribute levels; and
x_i = specific level of attribute X_i.