Integrated Multiple Objective-Attribute Methodology to Determine the Overall Value of Implemented New Technology in Transportation

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Stephen P. Mattingly
R. Jayakrishnan
Michael G. McNally

Department of Civil and Environmental Engineering and Institute of Transportation Studies
University of California, Irvine
rjayakri@uci.edu, mmcnally@uci.edu

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Institute of Transportation Studies
University of California, Irvine
Irvine, CA 92697-3600, U.S.A.
http://www.its.uci.edu
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Stephen P. Mattingly
Graduate Student Researcher
Department of Civil and Environmental Engineering
University of California, Irvine, CA 92697, U.S.A.
949-824-6571
e-mail: spmatt@translab.its.uci.edu

R. Jayakrishnan
Associate Professor
Department of Civil and Environmental Engineering
University of California, Irvine, CA 92697, U.S.A.

Michael G. McNally
Associate Professor
Department of Civil and Environmental Engineering
University of California, Irvine, CA 92697, U.S.A.

ABSTRACT

This paper integrates two existing techniques and creates a methodology for evaluating transportation projects, especially complex projects involving new technologies. While integrating the multiple-attribute value function (MAVF) technique with the analytic hierarchy process (AHP), the authors introduce a new scaling approach through use of a "linear scaling proxy." Additionally, the authors' approach identifies an "overall worth" for a project. This "overall worth" provides decision-makers with a quantitative value that they can use to compare different projects or estimate and compare hypothetical results. The authors demonstrate this methodology in a sample problem. Then, the authors describe the methodology's application to the Anaheim Field Operational Test. Often, evaluations fail to look at all of the potential areas that a project impacts. This methodology simplifies the process for including institutional issues into the final results of an evaluation.

Key Words:
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I. INTRODUCTION

The need for evaluation exists in many areas of the transportation field. Evaluation can look at two different situations. In one example, an agency needs to select a course of action from multiple alternatives. This example might include choosing between multiple construction or retrofit options. Another type of evaluation wants to identify the impact of a previously implemented change. Agencies may choose to alter the routes for buses, commercial vehicles or airplanes, change the existing infrastructure, or modify the traffic control system. Often, these evaluations address only the technical or performance aspects of these changes. Alternatively, some agencies use a simple cost-benefit analysis to evaluate a specific project. This approach may fail to capture all of the impacts of using multiple decision makers as well as attributes. Furthermore, cost-benefit analysis may not adequately identify the relationships between attributes and objectives. In rare cases agencies may choose to use techniques such as the analytic hierarchy process (AHP) (Saaty, 1977) used commonly in business decision-making to decide on one option. Theoretically it is also possible to use value functions derived from subjective and preferential information, to evaluate a smaller part of a project with clearly identifiable multiple performance attributes, as in multiple-attribute value function (MAVF) techniques (Keeney and Raiffa, 1993), though application of this techniques have been ever rarer. No comprehensive approach exists however for evaluating and finding objective overall worth of transportation projects, possibly among the most complicated decision/evaluation problems that any analyst can face. The complexities are a direct result of the multiple agencies, multiple actors, multiple users, multiple funding sources, in both public and private sectors which are part of any transportation project. This especially so in the case of the several new technology implementation projects currently underway in the US and around the world, which motivates the research in this paper. Finally, the need for detailed evaluations in the transportation field should increase in the future as more agencies implement new Intelligent Transportation Systems (ITS) technologies which use new approaches and are often implemented incrementally by modifying existing technologies.

Whenever an agency chooses to use a new technology they need to determine if it lives up to their expectations by identifying all of its impacts, both positive and negative. Often, agencies find it difficult to examine the institutional implications or impacts of new technologies in an objective manner in conjunction with measurable impacts as in selected performance criteria or cost. Such institutional aspects would include inter-agency cooperation among multiple public agencies involved, as well as public and political response to the projects. Strong evaluations may allow agencies to develop new operating policies and examine existing ones. Additionally, other agencies need to examine the new installations to recognize the factors that may impact the same technology's implementation within their
agency (the issue of "transferability"). This information can prove invaluable in the decision-making of all agencies that use a specific technology, may want to use a specific technology or may want to combine multiple technologies together.

The expansion of ITS technologies creates the need for formal evaluations of these new technologies. The Federal Highway Administration (FHWA) provides vendors and public agencies the opportunity to test new ITS technologies through their Field Operational Test (FOT) Program. While the vendors want to prove their product's value, and the public agencies want to improve their traffic conditions, the FHWA wants an evaluation of the new technology's contribution to the ITS America National Program Plan. As a result, each FOT requires its own evaluation; therefore, these FOT evaluations and future evaluations of ITS technologies need an effective and efficient approach that allows evaluators to determine the overall worth of both an entire installation of ITS technology and each individual technology. In order to establish an ITS technology's net value, the researcher has to determine its impacts on network performance, its relationship with the infrastructure, and its effects on the institutional environment. The research approach described here addresses these areas of concern and presents a methodology that yields such an overall worth measure by combining preferential information from the actors involved such as agencies, decision-makers, and the users in an integrated fashion with the multiplier objectives, and multiple attributes involved therein. While no claim can be made that this is the perfect solution to the problem at hand, it is a useful and methodologically appealing technique that directs evaluations towards reasonable and comprehensive conclusions.

In this paper we present a methodology that begins by developing a hierarchy of all the pertinent facets of the evaluation. The key aspect of this is a newly developed concept of combining the Analytical Hierarchy Process (AHP) with multi-attribute value functions (MAUF). We integrate these two techniques by using the values obtained through the AHP process as additional weights for the attributes in the multi-attribute value function. This is, to our knowledge, the first attempt at such an integration of these techniques in the decision and evaluation research. Furthermore, this paper introduces a method for providing different value functions with the same scale so that they can be combined to find a single value for the overall evaluation. The technique used here is based on what we call a "linear scaling proxy", which is a significant new concept that allows the integration of two diverse techniques in decision-making, the AHP and MAUF. As explained in this paper, such a scaling-proxy technique is particularly applicable to transportation evaluation while it may not be for other evaluation problems. The focus in the paper is to present the scheme with clear methodological foundations, not just to describe how to apply the method.

This paper briefly reviews some previous FOT and ITS evaluation research. The next section covers the methodology that this technique requires and introduces. We then describe and solve a sample problem, in this case an evaluation of a bus transit routing scheme. The simpler sample problem is chosen for easier elucidation of the methodology, as compared to the more complicated new ITS
technology evaluation problem. The next section however outlines the methodology's application to the existing Anaheim and Irvine FOT evaluations, though without a complete application as the Field Operational Test projects in California where the technique is being currently applied is only nearing completion. Finally, the paper discusses methodological implications and provides conclusions.

**Literature Review**

In this section we briefly examine the available work specifically in the area of new technology implementations and Field Operations Tests (FOTs) in transportation. The literature in the area of general decision making and evaluation, as developed by operations researchers and business decision analysts is much too vast for the scope of this paper; however, references to key literature are provided below in section II dealing with the methodology.

The working paper by Bolczak (1993) should be considered as among the first to provide some basic guidelines for a FOT evaluation framework; however, this paper fails to deal with the evaluation process itself in any great detail. Known informally as the "MITRE guidelines", it did provide initial stimulation for evaluation schemes used in many FOTs recently. Furthermore, Booz-Allen and Hamilton, Inc. (BAH), Washington, D.C. have provided additional evaluation support and some modified techniques as a Federal Highways Administration (FHWA) consultant. Using the concepts that Bolczak (1993) outlines, BAH reviews and provides comments to all evaluation documents associated with a FOT.

A few other researchers have recently looked at ITS evaluation; however, much of their research focuses on evaluation at the planning level. For example, Brand (1994) uses a multi-criteria approach for selecting the appropriate operational tests for funding. Additionally, he creates a large list of candidate criteria for evaluators to select from for their specific evaluation. Levine and Underwood (1996) use a modified AHP to determine ITS planning goals. Furthermore, they look at multiple stakeholders as opposed to a single decision-maker. While evaluation for ITS planning purposes may introduce interesting techniques, it fails to address an evaluation's results. The results of a previously conducted operational test serve as one of the best planning aides possible. Underwood and Gehring (1994) provide a better look at the techniques available for evaluating specific ITS projects. They discuss different types of evaluation and recommend types of data sources for seven different objective categories. Hall, Miller, and Khattak (1996) discuss the steps associated with evaluating the effectiveness of integrated traffic corridors. Their research looks at developing an evaluation plan, selecting data sources, and data collection techniques. They never executed this evaluation plan because they experienced institutional difficulties. The final two papers provide assistance to the evaluator developing an evaluation plan by filling in some of the procedural details that Bolczak (1993) did not focus on in his original evaluation guidelines.
II. METHODOLOGY

We develop a hierarchy for the factors and attributes that influence a given problem or evaluation scenario. Here a “factor” could be an objective, a criterion, or even an operational condition of the project that requires separate evaluation. For instance, institutional and performance objectives could be separate factors; so could be the technology’s worth under peak vs. off-peak traffic conditions. We select the attributes so that the evaluation covers every facet of a project, the attributes being the primary variables which describe and determine the factors under consideration. The proposed methodology uses an individual value function for each branch in the hierarchy and uses the analytic hierarchy process to provide weights for each branch. Furthermore, we introduce a new technique for combining the multiple value function associated with each branch into a single final value. We next describe the methodology involved in MAUF techniques, AHP techniques and then the newly introduces linear scaling proxy that is necessary to comprehensively combine the two schemes.

Multi-Attribute Value Functions

Multi-Attribute Value Functions (MAVF) enable the researcher to evaluate and combine multiple attributes to arrive at an overall value function. This method develops a value function that provides a weight for every attribute. We use the evaluation results as the data for each attribute in the value functions. This approach can only use attributes based on a continuous, ratio scale. Many of the institutional attributes are not represented on a continuous, ratio scale; therefore, proxy variables are needed to capture these attributes. Although the use of proxy variables is a straight-forward procedure, Keeney and Raiffa (1993) provide a more detailed description of their use.

First, this paper looks at the existing method. Value functions can only be used in situations involving no uncertainty; this situation corresponds directly to evaluating a new technology because the values for the attributes are often known with certainty. Multi-attribute utility functions (MAUFs) that incorporates uncertainty can potentially be incorporated in the scheme here, but are not attempted in this paper. In order to determine a MAVF, the analyst needs to decompose the multi-attribute function into single-attribute functions where every attribute is represented individually. The researcher can develop a simple additive function, the simplest method available, to combine these functions to form the MAVF. In order to use this method, the attributes must meet the so-called “corresponding trade-offs condition” (Keeney and Raiffa, 1993). In order to meet this condition, if for two attributes, \( x_1 \) and \( x_2 \), an increase of \( a \) in the value of \( x_2 \) is worth \( b \) units of \( x_1 \) regardless of the values of \( x_1, x_2, a \) and \( b \). Additionally, when the analyst looks at more than two attributes the “mutual preferential independence” must apply. This condition states that a pair of attributes, \( x_1 \) and \( x_2 \), is preferentially independent of \( x_3 \) if the preferences for \( x_1 \) and \( x_2 \) do not depend on \( x_3 \)’s value. If the value functions for \( n \) attributes meet the previously discussed requirements, then their additive value function takes the form:
\[ v(x_1, x_2, \ldots, x_n) = \sum_{i=1}^{n} v_i(x_i) \]  

Keeney and Raiffa (1993) discuss two techniques for obtaining the value functions \( v_i(x_j) \) for every attribute \( x_i \) and the corresponding weights between these value functions, from interviewing a “decision-maker”, which could be an actor such as a representative of the city agency involved in the project, or the FHWA project manager who is in charge of funding the project, or a plain user of the technology. One technique, mid-value splitting, looks at the potential range of values for a given attribute across all alternatives. This technique asks the decision-maker to determine the midvalue point along this range. Then, the decision-maker must select the midvalue of the two new regions that he or she just created. Unfortunately, this technique can not be applied to an evaluation problem because the evaluator does not always know the potential range of values for a given attribute prior to the evaluation (such as, for instance, what the maximum delay resulting from a new traffic control technique can be). Therefore, evaluation research needs to look at using the lock-step procedure. In this procedure, a decision-maker compares two attributes with one another. Increases or decreases in one attribute are traded off with increases or decreases in the other attribute. This procedure intertwines the two attributes because their values relate to each other. Furthermore, the evaluator establishes the existence of the corresponding tradeoffs condition between two attributes while implementing this procedure. Once a sequence of questions are asked, it is a rather straight-forward procedure to find a few sample points on value function, the function itself then determined with a polynomial curve fitting. These techniques are rather standard in MAUF schemes.

**Analytic Hierarchy Process**

Although the MAVF technique is used to handle the values attached to subjective attributes, MAVF fails to handle comparisons between subjective factors; therefore, we use the analytic hierarchy process (AHP) in incorporate the comparisons between factors such as objectives and criteria, elicited during the interview process. Thomas Saaty introduced AHP in the mid-1970s (Saaty, 1977, 1980, 1994) as a general purpose approach to multiple criteria decision making, which is based on mathematical properties of comparison matrices that makes it easy to derive weights using straightforward analytical schemes. Saaty bases AHP on three principles: decomposition, comparative judgments, and the synthesis of priorities. The decomposition principle requires that the problem be broken down into a hierarchy. This hierarchy begins broad and becomes more specific on each lower-level. The relationship of the elements on different levels must conform to certain independence and dependence requirements. The principle of comparative judgments makes pairwise comparisons of elements within a level with respect to
the next-higher level. These comparisons combine to form matrices. The synthesis of priorities principle constructs a composite set of priorities for the elements at the lowest level of the hierarchy.

AHP starts with the organization of the attributes and factors into a hierarchy. After establishing the hierarchy, the analyst asks the decision-maker to make pairwise comparisons of elements with respect to the component on the next-higher level. These comparisons use Saaty's AHP Importance Scale (Table I), which is rather rigidly adhered to, due to certain logical reasons considered important by Saaty. The pairwise comparisons require judging on a relative scale: therefore, the preference of A to B is the reciprocal of the preference of B to A. These comparisons form a matrix of the form found in Table II. AHP determines the local priorities for each level by calculating the normalized principal eigenvector., which is where the mathematical priorities attain certain physical meaning.

Table I. AHP IMPORTANCE SCALE (Saaty, 1982)

<table>
<thead>
<tr>
<th>Intensity of Importance</th>
<th>Definition</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Equal importance of both elements</td>
<td>Two elements contribute equally</td>
</tr>
<tr>
<td>3</td>
<td>Weak importance of one element over another</td>
<td>Experience and judgment slightly favor one element over another</td>
</tr>
<tr>
<td>5</td>
<td>Strong importance of one element over another</td>
<td>Experience and judgment strongly favor one element over another</td>
</tr>
<tr>
<td>7</td>
<td>Demonstrated importance of one element over another</td>
<td>An element is strongly favored and its dominance is demonstrated in practice</td>
</tr>
<tr>
<td>9</td>
<td>Absolute importance of one element over another</td>
<td>The evidence favoring one element over another is of the highest possible order of affirmation</td>
</tr>
</tbody>
</table>

Table II. AHP Pairwise Comparison Matrix

<table>
<thead>
<tr>
<th></th>
<th>Alt 1</th>
<th>Alt 2</th>
<th>Alt 3</th>
<th>Alt 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alt 1</td>
<td>1</td>
<td>1/a</td>
<td>1/b</td>
<td>1/c</td>
</tr>
<tr>
<td>Alt 2</td>
<td>a</td>
<td>1</td>
<td>1/d</td>
<td>1/e</td>
</tr>
<tr>
<td>Alt 3</td>
<td>b</td>
<td>d</td>
<td>1</td>
<td>1/f</td>
</tr>
<tr>
<td>Alt 4</td>
<td>c</td>
<td>e</td>
<td>f</td>
<td>1</td>
</tr>
</tbody>
</table>

AHP also provides a measure of the decision-maker's judgment, which checks if the elicited preferential information follows the reciprocal requirement. Saaty refers to this measure as the consistency ratio, C.R.
\[
C. R. = \frac{\lambda_{\text{max}} - N}{(N - 1)(R. I.)}
\]  

(2)

Saaty (1980) approximates the Random Indices (R.I.) for various matrix sizes using simulation. Mollaghasemi and Pet-Edwards (1997) refer to consistency ratios less than 0.1 as acceptable. If a decision-maker's responses fail the consistency test, then the analyst must re-question him or her until obtaining consistent responses.

AHP represents one of the more popular forms of multicriteria decision-making. Some experts have expressed concerns about some features of AHP in the past; however, the benefits that it provides to this research is often considered to outweigh the negatives. We believe that AHP provides a simple process for weighting portions of the hierarchy that can not be enumerated by data directly.

**Linear Scaling Proxy**

A significant scaling problem exists when combining multiple value functions. The techniques for generating an additive value function, the lock-step approach and mid-value splitting, identify a common scale for each attribute. We need to combine multiple separate value functions at the bottom "leafs" of the AHP hierarchical "tree" structure with the AHP-generated weights along the tree to derive a final value for the problem (the reader may glance at the example problem in the next section to see such a structure). Note that a separate additive value function is found by combining the individual value functions of the set of attributes at each such "leaf". For the overall value found over the whole tree to be reasonable, however, the value functions across these "leafs" should have a common scale. In order to create a standardized scale, we propose a linear scaling proxy for this. We select a proxy attribute, the linear scaling proxy, that has a linear relationship with at least one of the attributes, in each additive value function (at each "leaf"). The relationship between the scaling proxy and the key attribute must be linear in order to retain a common scale for each of the value functions. If a nonlinear relationship exists, then the value functions cannot be combined using this proxy. Every attribute in the separate value functions need to be related to the key attribute using the lock-step approach. After setting-up the value of each function using the key attribute's scale as scale for the function.

For example, the analyst proposes a model that has three separate value functions, \(V_1\), \(V_2\), and \(V_3\). Each of these value functions has an attribute, \(a_i^{key}\), that has a linear relationship with the scaling proxy, \(p_i\).

\[
p_i = m_i(a_i^{key}) + b_i \quad \text{for} \quad i = 1,2,3
\]  

(3)
After establishing the linear relationship between $p$ and $\alpha_i^{key}$ by solving for $m$ and $b$, the value functions can be converted to a common scale using the following equation.

$$V_i = m_i(V_j) + b_i \quad \text{for} \quad i = 1,2,3$$ (4)

Based on our experience, the intercept value $b_i$ will often be equal to zero and drop out of the equation. The question arises whether such a common scaling proxy would always exist across all the additive value functions. In most cases, a dollar value comparison appears possible with at least one of the attributes in each attribute set, especially in the case of transportation evaluation problems (it is important to note that there is no requirement that a dollar-value comparison be possible with all attributes). This new concept is what makes the approach possible, and makes it somewhat appropriate for transportation problems.

After converting every value function to the new standardized scale they can be integrated with AHP using the procedure outlined in the next paragraphs.

Integration

The MAVF and AHP schemes are combined to determine the final function that represents the decision-makers' preferences. The technique uses MAVF to handle all of the lowest-level attributes while AHP addresses the higher levels. The hierarchical approach here allows the analyst to account for the decision-makers' preference structure without creating brand new value functions for every possible combination. Furthermore, all of the attributes may not be comparable to one another in pairwise comparisons; however, the linear, scaling factor allows the analyst to combine multiple distinct value functions. The value functions represent the principal role in the evaluation because they establish a scale for comparing different types of data from the evaluation. The value functions retain their integrity while receiving a weighting structure from AHP.

The process begins with determination of the value function for every attribute. After determining these functions, the researcher needs to perform the AHP on the entire hierarchy, except for the attributes. After completing the AHP, the evaluator will have a the priorities for every objective. These priorities are used as weights for the attributes beneath each objective; therefore, the researcher must multiply each attribute's value function by the weight that corresponds to the appropriate objective. Given $n$ objective priorities ($O_1, O_2, O_3, \ldots, O_n$) and two attribute value functions for every objective $i$ ($A_{ij}$ and $A_{ij2}$), the new value function, $A_{ij}^{new}$, looks like:

$$A_{ij}^{new} = O_i(A_{ij}) \quad \text{for} \quad i = 1 \ \text{to} \ n, \ j = 1,2$$ (5)
The researcher needs to complete the integration process by performing this weighting procedures for every attribute in the hierarchy while remembering that some of the attributes may appear more than once. After completing the weighting procedure, the researcher may begin to apply the evaluation's results to each of the value functions.

III. SAMPLE PROBLEM

In this section, we outline and solve a simple, sample problem. Often, transit agencies make changes to either the number of buses on a route or the route that a bus follows. Usually, the agencies look exclusively at the technical aspects at these changes and fail to consider the institutional impacts. This example looks exclusively at the institutional impacts associated with creating a new bus route. This is only a hypothetical problem for illustrative purposes and the attributes and factors considered here are by no means exhaustive or even reasonable.

First, some primary attributes are selected: route acceptance, route safety, and transit system factors. Route acceptance factor is broken down into both passenger and driver acceptance. Route safety looks at safety in walking to the bus stop and safety while waiting at the bus stop. Transit system factors look at the quality of alternate transit routes, and links to other transit routes. Figure 1 outlines the proposed hierarchy. Here there are three “leaves” to the AHP tree, and a separate value function for each of the three sets of attributes (2 each at each “leaf”).

![Diagram of hierarchy]

Some of the six attributes listed above might be difficult to enumerate directly; therefore, we select proxy attributes for each of these. Driver acceptance uses the proxy of the hours required for drivers to become familiar with a new route. Passenger acceptance uses the proxy of the hours required for prospective passengers to become familiar with a new route. The quality of and familiarity with alternate transit routes attribute uses the amount of money spent on advertising to promote the new route as a proxy. Links to other transit routes uses the number of major attractions available along transit routes with a
maximum of one transfer. After selecting the attributes and proxy attributes for this problem, we need to select a linear scaling proxy attribute. For this problem, money (dollar value) is used as the linear, scaling proxy. The three key attributes for the three sets of two attributes each, are crimes/week at bus stops, advertising money spent, and time required for a driver to learn route. The evaluator questions the decision-maker to verify a linear relationship between each of the key attributes and money while determining the relationships' nature. Table III presents the sample preference structure (reciprocal matrix) elicited from the hypothetical transit decision-maker, and the resulting weights from the AHP analysis.

Table III. AHP Preference Structure and Resulting Weights

<table>
<thead>
<tr>
<th></th>
<th>Route Acceptance</th>
<th>Route Safety</th>
<th>Transit System Factors</th>
<th>Weights</th>
</tr>
</thead>
<tbody>
<tr>
<td>Route Acceptance</td>
<td>1</td>
<td>1/3</td>
<td>3</td>
<td>.260</td>
</tr>
<tr>
<td>Route Safety</td>
<td>3</td>
<td>1</td>
<td>5</td>
<td>.633</td>
</tr>
<tr>
<td>Transit System Factors</td>
<td>1/3</td>
<td>1/5</td>
<td>1</td>
<td>.106</td>
</tr>
</tbody>
</table>

The consistency ratio for this preference structure is 0.011 which is less than 0.01; therefore, the decision maker's responses seem consistent. Figure II. presents the value functions determined from the decision maker interviews using the lock-step technique and polynomial curve-fitting. This problem discovered the following linear relationships between the scaling proxy and key attributes where $1,000 is equal to one value point.

- 1 Crime at a Bus Stop = 25
- Advertising Money (in 1,000,000s) = 0.001
- Time required for a driver to learn a new route (in hrs) = .45

After the initial evaluation, the decision-makers decided to look at a hypothetical example where the transit agency decreased crime at their bus stops along the same route. Table IV Outlines the data for this problem, and Table V presents the solution.
Figure 1. Value Function of Crimes/Week at Bus Stop

\[ y = -0.0155x^2 - 0.0818x \]
\[ R^2 = 0.9885 \]

Figure 2. Value Function of Crimes/Week While Walking to Bus Stop

\[ y = -0.0002x^2 + 0.0063x - 0.1708x \]
\[ R^2 = 0.9943 \]

Figure 3. Value Function of Advertising Money

\[ y = 0.073x^2 - 1.2042x \]
\[ R^2 = 0.9955 \]

Figure 4. Value Function of Major Attractors Available with one or Fewer Transfers

\[ y = -0.0019x^2 + 0.2012x \]
\[ R^2 = 0.9998 \]

Figure 5. Value Function of Time Required for a Passenger to Learn Route

\[ y = 0.1125x^2 - 1.7494x \]
\[ R^2 = 0.9998 \]

Figure 6. Value Function of Time Required for a Driver to Learn Route

\[ y = -0.0006x^2 + 0.0346x \]
\[ R^2 = 0.9995 \]
Table IV. Data for Sample Problem

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Existing System</th>
<th>Hypothetical System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crimes/week at Bus Stops</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Crimes/week while Walking to Bus Stops</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Advertising Money (in 1,000,000s)</td>
<td>.125</td>
<td>.125</td>
</tr>
<tr>
<td>Major Attractors Available Within One Transfer</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Time Required for a Passenger to Learn the Route (hrs)</td>
<td>.75</td>
<td>.75</td>
</tr>
<tr>
<td>Time Required for a Driver to Learn the Route (hrs)</td>
<td>24</td>
<td>24</td>
</tr>
</tbody>
</table>

Table V. Sample Problem Solution

<table>
<thead>
<tr>
<th></th>
<th>Existing System</th>
<th>Hypothetical System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Route Safety Scaled Value Function Total</td>
<td>-161</td>
<td>-127</td>
</tr>
<tr>
<td>Route Safety Value (after AHP weighting)</td>
<td>-102</td>
<td>-81</td>
</tr>
<tr>
<td>Route Acceptance Scaled Value Function Total</td>
<td>-18</td>
<td>-18</td>
</tr>
<tr>
<td>Route Acceptance (after AHP weighting)</td>
<td>-5</td>
<td>-5</td>
</tr>
<tr>
<td>Transit System Factors Scaled Value Function Total</td>
<td>17413</td>
<td>17413</td>
</tr>
<tr>
<td>Transit System Factors (after AHP weighting)</td>
<td>1849</td>
<td>1849</td>
</tr>
<tr>
<td>Total Value</td>
<td>1742</td>
<td>1763</td>
</tr>
</tbody>
</table>

The decrease in crime has less than a two percent affect on the route’s value. Transit system factors dominate the evaluation because the decision-maker believes that connecting a route to major attractions makes a route extremely appealing. However, the decision-maker’s responses to the AHP priorities indicate that this may be an example of an inconsistency in the decision-maker’s responses. In this situation, the analyst may want to re-question the decision-maker. These results only discuss the institutional aspects of a new route and most decision-makers need to look at the infrastructure and technical aspects of a project when determining an overall evaluation.

IV. APPLICATION TO ANAHEIM/IRVINE FOT EVALUATION

The University of California at Irvine serves as a member of the evaluation team on two FOTs in Orange County, California. The researcher plans to use this methodology in the evaluation of these tests. The FOT in Anaheim, California, focuses on the implementation of the Split, Cycle, and Offset Optimization Technique (SCOOT) algorithm on top of the existing Urban Traffic Control System (UTCS). This FOT included a separate evaluation of a Video Traffic Detection System (VTDS) and an upgrade of UTCS to 1.5 Generation Control (GC) UTCS. The other FOT in Irvine, California, includes the integration of multiple technologies. The City of Irvine plans to implement the Optimized Policies for Adaptive Control (OPAC) algorithm to control an arterial corridor in South Irvine that parallels a freeway. The City of Irvine plans to use the Management Information System for Traffic (MIST) as their traffic management platform for this area. Additionally, Caltrans District 12 will introduce the System-Wide Adaptive Ramp Metering (SWARM) algorithms as their new ramp metering algorithms. This FOT
included a separate evaluation of the 2070 Advanced Traffic Controller (ATC) where OPAC will be installed. These FOTs provide the researcher with many technologies to investigate. Furthermore, the Irvine FOT allows the investigator to look at the interaction of multiple technologies.

Figures III, IV, and V present the candidate hierarchy for the Anaheim FOT. Clearly, this evaluation poses a more significant problem because of its size and its inclusion of multiple decision makers.

Figure III. Hierarchy for Anaheim FOT

```
Overall Value
For The Anaheim FOT

Technical Issues                Institutional Issues

Special Events                  Non-Special Events

Entry to Event                  Egress from Event
  |                                 |
  | B                                 |

Peak Period                      Off-Peak Period
  |                                 |
  | B                                 |
```

Figure IV. Institutional Issues

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A

Administrative Issues
Personnel Issues
Financial Issues
Legal and Liability Issues
Technical Issues

Project Management
Inter-Agency Coordination
Budget
Training
Maintenance
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V. METHODOLOGICAL DISCUSSION

The most important aspect of the technique presented is its flexibility to incorporate various dissimilar factors, objectives and attributes into a simple, elegant and comprehensive scheme. The technique does not purport to provide the “most correct” possible overall worth of any evaluation; however, this should be taken in the context of there being no such single value that can be considered the “most correct” due to the subjective nature of several of the attributes, and objectives involved. However, the two techniques (AHP and MAUF) being combined here, to our knowledge for the first time, have both undergone several years of methodological scrutiny. There have been criticisms on these two techniques in decision-theory research, but they have both been accepted to a large extent by academicians and perhaps to a larger extent by practitioners.

The concept of a linear scaling proxy requires at least one attribute in each attribute-set to be linearly scaleable and preferentially comparable with the proxy. This new technique does not pose a constraint on the application, but rather directs the analyst towards more careful grouping of factors and attributes. The flexibility provided by the scheme also extends to introducing levels in the hierarchy that comprise operational conditions. Note that even standard statistical test design matrices used in Analysis-of-Variance (ANOVA) studies can be incorporated into this evaluation scheme (such as overall worth under congested conditions for a new traffic control technology compared to the overall worth under non-congested conditions).

Group decision making can be incorporated into this method using two possible general approaches and the numerous variations that exist when combining the two approaches. One method involves gathering all of the decision-making group into a single forum. In this forum, the evaluator asks the same questions that he or she uses in the individual case, but this time the group discusses the question and their responses to arrive at a final response. The other general method involves asking each member of the group to determine their own individual preference structure that the analyst combines together to
form the group's overall preference structure. Furthermore, some individuals within the group may not be qualified to provide their preferences for all of the attributes within an evaluation. When this situation arises, these individuals can be excluded on an attribute by attribute basis. Frequently, this technique lends itself towards the second general approach so that multiple group forums do not have to be formed that exclude certain members for specific attributes. Finally, the evaluator may choose to combine the two general methods. In this situation, the evaluator may have a group forum respond to either the AHP preference questions or the value function preference structure. This method easily adapts to the approach that an evaluator wants to use for the group decision-making problem.

A significant criticism that exists whenever using AHP is that of its possibility to show rank reversal while ranking alternatives. That is, if the analyst introduces new options or elements to the hierarchy, the preference order may not be preserved. This problem can potentially exist in applications of our scheme, as well, if the factors considered are not sufficiently dissimilar. However, transportation evaluation problems are usually one-time applications in large projects, as compared to business decision-making where the same models are repeatedly used under various conditions, and as such the problem of rank reversal may not occur in transportation applications. This issue remain to be studied in detail, however.

VI. CONCLUSIONS

We use existing techniques as the starting point for this research, but introduce some significantly new approaches to integrate the approaches in this paper. In multi-attribute decision-making, decision-makers attempt to maximize their value functions; however, multi-attribute evaluation does not allow any changes in the attribute values because the evaluation provides this data. We identify a quantitative “worth” of the existing system. The ability to determine a quantitative value for an evaluation provides decision makers with a meaningful result that they can compare to other possible results.

The new linear, scaling proxy allows an evaluator to combine the values determined from multiple value functions with different scales into one overall value. This technique permits the analyst to create an overall value for the project. This new technique can provide an analyst with greater flexibility as he or she selects the appropriate attributes for the evaluation.

Finally, we create a hybrid of AHP and MAVF. By combining the two techniques, the researcher can reduce the quantity of items that must be compared directly. Furthermore, the evaluator can use the evaluation's actual data to determine each technology's and the system's total "worth." If the evaluator uses only the AHP, he or she has to present the results of the entire evaluation to the decision-makers before beginning the decision-maker forum. Furthermore, the decision-makers can only choose between the alternatives that the evaluation addresses directly. The MAVF provides the evaluator with the flexibility to examine multiple alternatives while establishing the decision-makers' preference structure prior to the completion of the evaluation process. However, performing pairwise comparisons for the
entire set of attributes seems cumbersome. The MAVF approach alone requires a greater number of attributes because the evaluator needs to identify the preferences between the objectives, technologies, and conditions that impact multiple attributes. Our hybrid scheme solves these problems by combining the two approaches.

VII. REFERENCES


