High-Precision Prioritization Using Analytic Hierarchy Process: Determining State HPMS Component Weighting Factors

RONALD F. HAGQUIST

The analytic hierarchy process (AHP) is a scoring procedure that uses a high-precision method both for weighting criteria and comparing alternatives; the scores are scaled, summed, and normalized to give final "goodness" measures to the alternatives. These measures can then be the basis for selection, ranking, or allocation among the alternatives. The Highway Performance Monitoring System (HPMS) is a computer model that determines highway improvement needs by maximizing its "composite index," a performance measurement function that is a weighted sum of nine quantified highway condition factors for the sections of the road system. The weights are the relative priorities given to each of the condition factors. The results are sensitive to the component weights in this performance function, and some states have modified the national average default values in the model to better represent their own specific road condition priorities. Failure to represent these weights correctly would cause the model to optimize with the wrong priorities, producing a highway investment strategy inappropriate for that state. An empirical examination of the extent of uncertainty about what the index weights should be and whether AHP can improve the confidence of this determination relative to the usual single-step approach is presented. The study finds that because the AHP method does not produce the numerical biases seen in the single-step method, the AHP apparently yields these subjective preferences with greater precision. This is a promising approach for assessing competing multimodal projects, where a structured and rigorous method will be useful in scoring the alternatives and weighting the many criteria. These criteria will correspond to the necessarily multiple performance measures of a multimodal system such as time, cost, safety, reliability, and environmental impacts.

The Highway Performance Monitoring System (HPMS) is an analytical computer model developed in the late 1970s by FHWA and the states, originally to assess highway needs and costs nationwide. It is the basis for the FHWA biennial report to Congress *Status of the Nation's Highways and Bridges: Conditions and Performance* and subsequent evaluation of alternative budget proposals and legislative options. The HPMS system was used to define network designation and evaluation criteria for the Highways of National Significance Program. This program was the centerpiece for the post-1991 reauthorization of the federal-aid highway program; it was made available beginning in 1983 to states as a highway planning tool for their level of detail.

Using data from samples of highways, HPMS employs simulation and forecasting equations to analyze highway conditions, investment strategies, and user costs over given time periods.

Texas Department of Transportation, 125 East 11th Street, Austin, Tex. 78701.

HPMS uses a "composite index," a performance measurement function that is a weighted sum of nine quantified highway condition factors. The weights are the relative priorities given to each of the condition factors. The model can be run with no budget limit to determine total needs or with a constrained budget to determine the priority set of highway improvements. However, the model is highly sensitive to the component weights in this performance function, and some states have begun modifying the "national average" default values in the model in an attempt to represent their own specific road condition priorities. Failure to quantify these priorities correctly would cause the model to optimize with the wrong factors, producing a highway investment strategy inappropriate for that state.

Rational determination of priorities (and weightings) is one of the classical problems in the field of operations research. Major advances in decision science have melded the mathematics and psychology of the decision process. These advances centered on the analytic hierarchy process (AHP) developed by Thomas Saaty. This research paper examines the extent of agreement about what the index weights should be and whether AHP can improve the confidence of this determination relative to the usual single-step approach.

The paper is composed of three sections. The first is an analysis of the sensitivity of the HPMS model to changes in the composite index component weights. The second section is a brief exposition of the AHP as used for determining these weights. The third section presents the empirical results of using AHP to determine the weights relative to the usual single-step approach.

HPMS MODEL SENSITIVITY TO COMPONENT INDEX WEIGHTS

The HPMS model allows four procedures for arriving at a priority ranking of highway improvements or capacity increases (*1*,p.III-1). One of these procedures is its composite index, a weighted sum of the values of the following condition factors as given in Table 1.

In algebraic terms, the composite index is the sum of the values of each component times its weighting. There is an established range of measurable values for each component, and the component weights sum to unity:

$$CI = \sum (w_i)(r_i)$$

$$\sum w_i = 1$$

where w_i equals the index component weight and r_i is the rating with respect to that component.

When the composite index procedure is chosen, the model selects those highway improvements that maximize the value of this index, the process shown in Figure 1. It follows that the weights given the components will affect the model output: the total improvement needs relative to capacity needs, and the priority mix of recommended actions.

The expert system module is used in place of a formal multiperiod optimization algorithm. This module recommends investment policies based on heuristic guidelines similar to those that an experienced engineer might use.

The New Jersey Department of Transportation has examined the sensitivity of its state HPMS model to trade-offs among sets of the index components (2). The sets were as follows:

- Condition factors:
  - –Pavement type,
  - –Pavement condition, and
  - –Drainage adequacy.
- Safety factors:
  - –Lane width,
  - –Shoulder width,
  - –Median width, and
  - –Alignment adequacy.
- Service factors:
  - –V/C ratio, and
  - –Access control.

Figure 2 shows the sensitivity of the total highway needs assessed by the HPMS model for the New Jersey highway system. A reversal of emphasis between condition and safety factors from 90/5 to 5/95 (the first and last bars) results in a change of almost $1 billion in assessed highway project needs.

Figure 3 shows the sensitivity of the total vehicle operating costs assessed by the HPMS model for the New Jersey highway system. A reversal of emphasis between condition and safety factors from 90/5 to 5/95 (the first and last bars) results in a change of about $10 billion in assessed vehicle operating costs over the 18-year planning period.

TABLE 1 Composition of HPMS Composite Index

CONDITION FACTOR	IMPORTANCE WEIGHT	APPRAISAL RATING	FACTOR SCORE
Pavement Type	W_1	R_1	W_1R_1
Pavement Condition	W_2	R_2	W_2R_2
Drainage Adequacy	W_3	R_3	W_3R_3
Lane Width	W_4	R_4	W_4R_4
Shoulder Width	W_5	R_5	W_5R_5
Median Width	W_6	R_6	W_6R_6
Alignment Adequacy	W_7	R_7	W_7R_7
V/C Ratio	W_8	R_8	W_8R_8
Access Control	W_9	R_9	W_9R_9
Composite Index			$\sum_{n=1}^{9} W_nR_n$

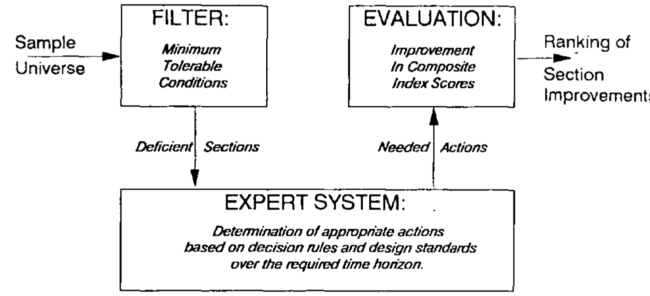

FIGURE 1 HPMS model logic.

Some states use the default weights, which are the national average numbers that come with the HPMS model. Others change the weights in a one-step process using intuitive judgment about the relative magnitudes of the appropriate numbers (3). An alternative to this one-step determination is the AHP.

ANALYTIC HIERARCHY PROCESS

Operations research (also called management science) is a discipline dedicated to the development of techniques to help decision makers deal with the increasing complexity of the world. Utility theory, trade-off analysis, and the Delphi process represent contributions to aspects of this problem from the respective disciplines of economics, engineering, and management. During the 1980s there were major advances in combining these approaches, melding the mathematics and psychology of the decision process. These advances centered on the AHP, producing a rigorous yet simple mechanism for better evaluating alternatives using multiple criteria. AHP-based software is now widely used for selection decisions, prioritizing, and budget allocation.

Saaty, the developer of AHP, was a mathematician working on an analytical framework for group decisions for the Departments of Defense and State during the 1970s. He was able to determine the structure and basic logic of the natural decision-making process and then to find the mathematics most appropriate to build a model of this process. Research had already shown that complex decisions are beyond the capacity of the brain to analyze. For example, a classic study by Miller in the 1950s demonstrated that humans can deal with only about seven items at a time. When the AHP is used, a decision problem with too many criteria and alternatives for the human mind to synthesize can be solved with the same natural intuitive logic that the human mind would use had it the capacity to deal with a problem of this size.

The AHP begins with structuring the decision problem much like an organization chart: with the overall goal at the top, the criteria and subcriteria next, and the alternatives at the bottom (Figure 4). Essentially a high-precision scoring procedure, the AHP multiplies each alternative score under each criterion by that criterion's weight and sums these to give a final composite score. These are scaled, summed, and normalized to determine "goodness" scores for the entire set of alternatives. These scores can

FIGURE 2 Sensitivity of total highway needs to composite index components (source: New Jersey Department of Transportation).

be the basis for selection, ranking, or allocation among the alternatives.

AHP differs from conventional scoring methods in the following ways:

- AHP uses a set of one-on-one comparisons to evaluate alternatives under each criterion. These pairwise comparisons are the smallest "quanta" of decisions.
- AHP uses one-on-one comparisons to assign criteria importance weights.
- AHP does alternative comparisons and criteria weighting in separate steps.
- AHP melds both objective measures and subjective preferences in the form of criteria weights. Typically, only the objective "facts" are quantified.

AHP has the following advantages over conventional scoring:

- The one-on-one comparisons increase the accuracy of the alternative comparisons. Research has found that such pairwise comparisons, properly averaged, can give a 400 percent increase in the precision of estimation.
- The one-on-one comparisons increase the accuracy of criteria weight estimations.
- The internal consistency of the alternative comparison process is quantified.
- The internal consistency of the criteria weighting process is quantified. Pairwise comparisons can contain contradictions among the direct and indirect comparisons.
- Subjective considerations are given a structured framework. Both subjective preferences and objective data are combined ex-

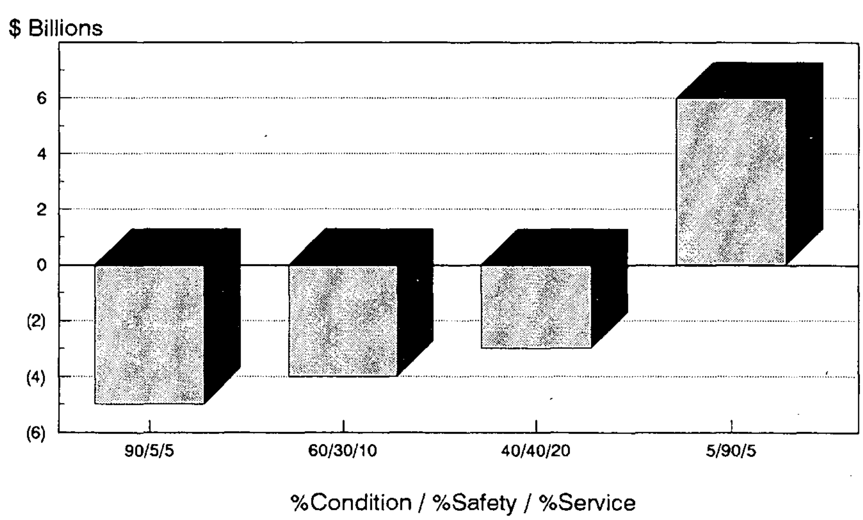

FIGURE 3 Sensitivity of vehicle operating costs to composite index components, over 18-year period (source: New Jersey Department of Transportation).

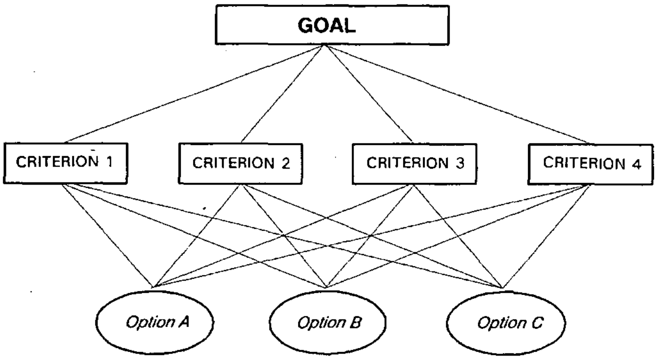

FIGURE 4 AHP structure.

plicitly, making the critical factors in the decision result much clearer.

- Sensitivity of the result is easy to analyze. The extent to which the key parameters can change before the result changes significantly can be seen quickly.

Using the commercial AHP software packages available—DecisionScience Plus, Expert Choice, Best Choice 3, Criterium, HIPRE—the only user input required is one set of pairwise comparisons among the criteria and another set among alternatives specified; the mathematics are internal to the program. These comparisons are facilitated by structured questions or dynamic visual graphics. Most software packages have sensitivity, what-if, and comparison consistency screens. Some allow many levels of criteria and subcriteria.

AHP has been used for private- and public-sector decision applications involving weighting, prioritizing, and selection. A recent literature search found 153 citations in 29 application areas (*4*,pp.39–40). For example, it was determined by Saito to be superior to other prioritizing techniques for highway bridge maintenance decisions (*5*). Empirical work by Foreman has found an improvement of about 400 percent in estimation accuracy by using AHP relative to the one-step process (*6*). In this study it is examined as an alternative to one-step weight assignment for HPMS model composite index components.

EXPERIMENTAL DESIGN

This project consisted of the following steps:

1. The subjects directly assigned weights to the components, which is the usual way that it is done: a one-step process to simultaneously assign weights to all the factors. To avoid possible bias, subjects were selected who had experience with highway issues but who were not familiar with the federal default values being used as weights. The questionnaire is given in Figure 5.

HPMS HIGHWAY CONDITION COMPOSITE INDEX FACTORS		
CONDITION FACTOR	DESCRIPTION	IMPORTANCE WEIGHTING (As a Percentage)
Pavement Type	The nature of road surface, ranging from unpaved to concrete/asphalt.	
Pavement Condition	The extent of roughness, cracking, potholes, and skid resistance.	
Drainage Adequacy	The absence of flooding, ponding, or erosion.	
Lane Width	The space allowed for vehicles in lanes.	
Shoulder Width	Space at the edge of the road available for emergency parking.	
Median Width	Space between opposing lanes of the road.	
Alignment Adequacy	Straightness of road, ranging from straight to hairpin curves.	
V/C Ratio	The traffic density of the road relative to its capacity.	
Access Control	The preference given to through traffic by limiting access.	
	Total	100%

FIGURE 5 Condition factor weighting questionnaire.

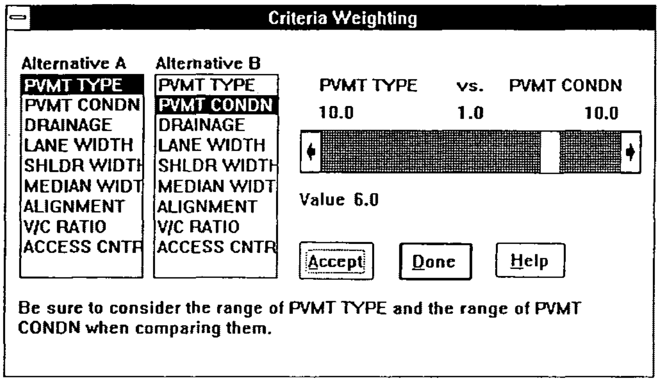

FIGURE 6 **Screen for pairwise weighting of condition factors.**

2. The subjects complete the AHP matrix of pairwise comparisons, a matrix of pairwise comparisons in which every factor is compared with every other factor once. This is a central feature of the AHP, making a set of one-on-one comparisons to view the factor comparisons in all possible ways and allowing redundancy in the process. Comparisons between each pair of factors was made on a scale of 1 through 10, where 1 meant that the pair was equal in importance and 10 meant that a factor was dominant in importance. Both a visual bar and numerical display were used to facilitate the comparisons shown in Figure 6.

3. Weights were calculated from the comparison matrix by the AHP eigenvector technique, the process of computing the factor weights from the set of pairwise comparisons using the eigenvector method, which effectively averages the matrix entries in all possible ways. An example of the averaged final weights for one of the participants in the following.

RESULTS OF WEIGHT ASSIGNMENT METHODS

Subjects were chosen who had experience and familiarity with the aspects of highway condition represented in the nine components of the HPMS composite index. They assessed appropriate weights using two basic methods: the customary direct assignment method, and then using AHP. These two sets of weights were then analyzed using standard statistical methods to determine their similarities and differences.

Single-Step Estimation

Pavement condition and volume-to-capacity (V/C) ratio had the highest average weightings, considerably above the other factors. As Table 2 indicates, there was substantial disagreement (measured as variance) among the respondents about many of the factor weightings, notably V/C ratio, pavement type, and pavement condition. There was also very close agreement that median width was the least important factor. Lane width, shoulder width, and alignment adequacy were factors with good agreement as well.

Figure 7 demonstrates the differences between the federal default values and the survey values. The largest absolute differences are for V/C ratio, pavement condition, and lane width.

A clearer demonstration of the significance of these differences is seen in the next chart of the differences expressed as percentage of the survey values. The greatest difference is for median width, but the difference is more than 50 percent for drainage adequacy, lane width, and V/C ratio. The average of the absolute values of the percentage differences is 39.7 percent, meaning that for Texas there was a substantial disagreement between the federal default values and the survey using single-step weight determination.

Figure 8 shows a significant bias in the numbers produced by the single-step method. It demonstrates the respondents' tendency to prefer numbers ending in 0's and 5's: 5, 10, 15, 20, and so forth. However, the ending number should be the numbers from 0 to 9 with approximately equal frequency. Instead, the subjects were extremely biased toward both 0's and 5's, with each being used about five times more than would be expected.

Additional bias can be seen in the distribution of numbers that do not end in 0's and 5's. The numbers closest to the "magic numbers" of 0 and 5 (1, 4, 6, and 9) are further reduced in frequency of selection relative to the numbers farther from 0 and 5. It appears that the desire to use 0's and 5's is so great that it suppresses the use of the numbers closest to them.

In summary, the frequency distribution for single-step weight selection demonstrates a strong bias toward two numbers and a skewed distribution among the other numbers.

AHP Estimation

The volume to capacity ratio had the highest average weight. As Table 3 indicates, there was substantial disagreement among the respondents about many of the factor weightings, notably V/C ratio. There was also high disagreement about alignment adequacy, drainage adequacy, and pavement condition. There was

TABLE 2 **Summary of Single-Step Process**

	PT	PC	DA	LW	SW	MW	AA	V/C R	AC
AVERAGE	10.7	20.1	7.9	9.1	7.3	6.2	10.5	19.9	8.4
VARIANCE	59.9	56.1	22.6	17.0	17.1	10.9	17.6	79.0	23.1

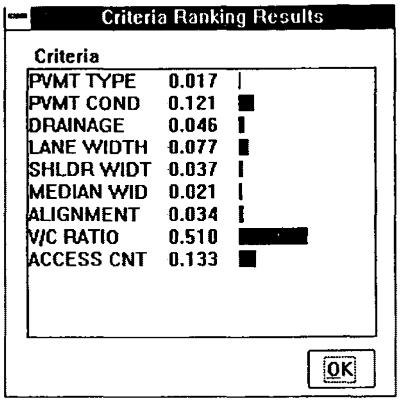

FIGURE 7 Screen showing final averaged condition factor weights.

close agreement that median width was the least important factor, and there was also close agreement about pavement type and lane width.

Comparison of Results

Table 4 presents the differences between the single-step and the AHP values. Since HPMS uses these values as weighting factors (i.e., as cardinal numbers), any differences would show up as changes in the improvements to the roadway system under a given budget. Figure 9 shows that the largest difference (as a percentage of the AHP values) was for pavement type, with other large differences for median width and shoulder width.

Using the non-parametric Kendall test for independence (*9*), the study finds that the ordinal rankings produced by the two approaches are positively correlated. This means that the two methods produce rankings that are similar, although not identical. However, the previous chart shows that there are substantial differences between the actual numerical weightings produced. The average of the absolute values of the percentage differences was 35.3 percent.

In addition, Figure 10 demonstrates that the AHP method does not show the strong numerical biases present in the single-step method. This could explain why the average variance for AHP was greater than for the single-step method, since in effect people are choosing from fewer possibilities when weighting in one step. This further suggests that the AHP method represents these subjective preferences with greater precision.

At the conclusion of the experiments, the participants expressed more confidence in the AHP method, citing its thoroughness in requiring that all pairwise comparisons of the factors be made. It appears that the factor weights are dependent on technique and that of the two approaches examined, AHP appears to be the method of choice.

CONCLUSIONS

Using a standard statistical test, the study finds that the ordinal rankings produced by the two approaches are positively correlated. This means that the two methods produce rankings that are similar. They are not identical, however, and there are substantial differences between the actual numerical weightings produced. The average of the absolute values of the percentage differences was 35.1 percent. In addition, the AHP method does not show the numerical biases present in the single-step method, where numbers ending in 0 and 5 are greatly overrepresented (Figure 11). This suggests that the AHP method represents these subjective preferences with greater precision and therefore is the method of choice to determine them.

HPMS use is not multimodal, but AHP is also a promising approach for assessing competing multimodal projects, where a precise method will be needed to establish the priority weightings for multiple criteria. These criteria will correspond to the necessarily multiple performance measures of a multimodal system such as time, cost, safety, reliability, and environmental impacts.

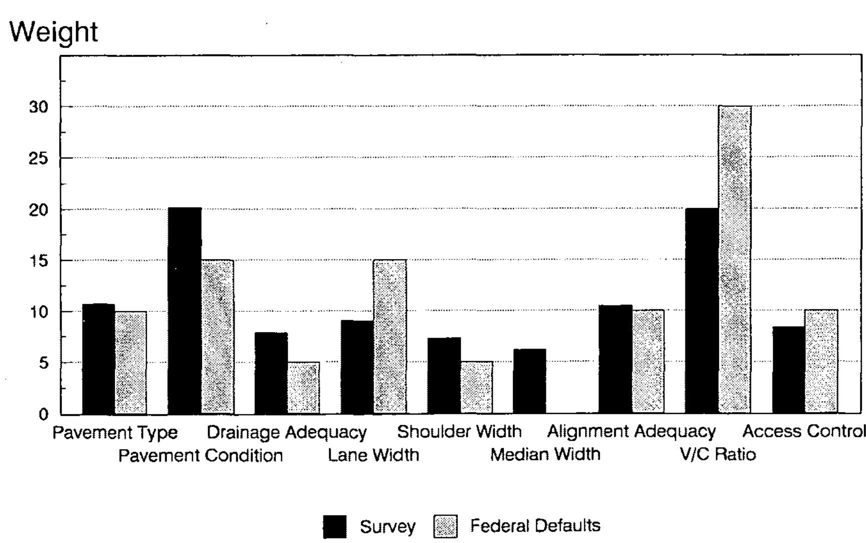

FIGURE 8 HPMS composite factor weights, survey results versus federal defaults.

TABLE 3 Summary for Analytic Hierarchy Process

	PT	PC	DA	LW	SW	MW	AA	V/C R	AC
AVERAGE	5.8	16.4	13.1	8.8	4.8	3.9	13.6	22.7	10.9
VARIANCE	22.4	76.8	85.5	11.9	20.2	12.1	87.8	147.8	67.0

TABLE 4 Combined Survey Results

	PT	PC	DA	LW	SW	MW	AA	V/C R	AC
SINGLE-STEP	10.7	20.1	7.9	9.1	7.3	6.2	10.5	19.9	8.4
AHP-PAIRWISE	5.8	16.4	13.1	8.8	4.8	3.9	13.6	22.7	10.9
DIFF'CE AS % OF AHP WT	85.1	22.4	-39.3	3.8	51.4	56.8	-23.0	-12.4	-23.5

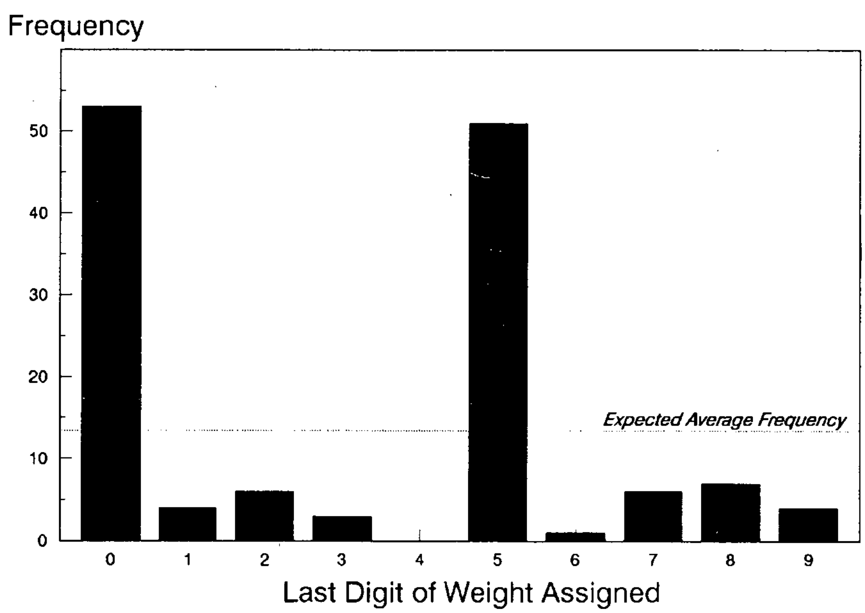

FIGURE 9 Bias of single-step weight assignment.

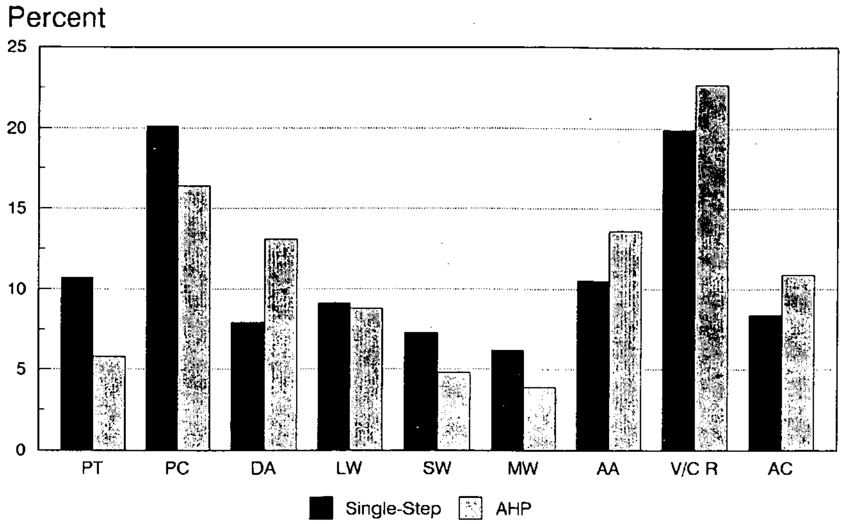

FIGURE 10 HPMS composite index factor weights, single-step method versus AHP.

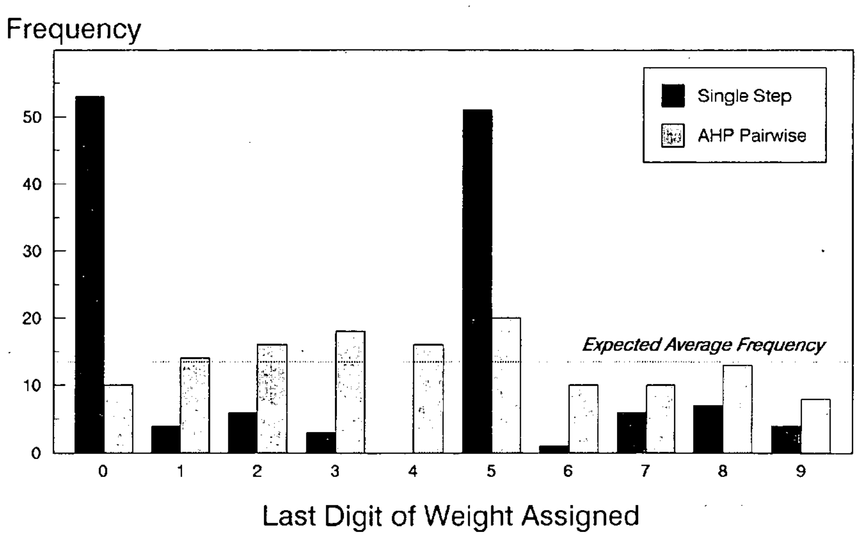

FIGURE 11 Bias of weight assignment methods.

REFERENCES

1. *The Highway Performance Monitoring System Analytical Process*, Vol. 1. FHWA, U.S. Department of Transportation, 1985.
2. Reilly, E. F. HPMS—New Jersey's Experience. Presented 1985.
3. *The Highway Performance Monitoring System Analytical Process: Examples of State Usage*. HPM-21. FHWA, U.S. Department of Transportation, 1989.
4. Saito, M. Application of the Analytic Hierarchy Method to Setting Priorities on Bridge Replacement Projects. In *Transportation Research Record 1124*, TRB, National Research Council, Washington, D.C., 1987, pp. 26–35.
5. Foreman, E. H. *Deriving Ratio Level Measures from Verbal Judgments* (in preparation).
6. Hollander, M. *Nonparametric Statistical Methods*. Wiley-Interscience, 1973, Ch. 8.

Publication of this paper sponsored by Committee on Transportation Programming, Planning, and Systems Evaluation.