

MODEL FOR EVALUATING BRIDGE CONSTRUCTION PLANS

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ABSTRACT: Effective planning has considerable influence on the successful completion of a bridge project, particularly with respect to minimizing effects on traffic flow, safety, and adjacent business activity. The optimization of such plans is, hence, desirable. However, designers lack objective tools with which to evaluate the effectiveness of their plans. This paper presents a model for evaluating bridge construction plans during the design phase. The model includes five major factors: safety, accessibility, carrying capacity, schedule performance, and budget performance. An additional 22 subfactors were developed to assist in evaluating these major factors. The model was developed based on observation of actual construction sites and through input from industry experts. It was validated through input from another set of industry experts and application to an actual bridge construction planning case.

INTRODUCTION

Optimizing the performance of urban freeway bridge construction projects demands that added attention be given to project planning. Construction sequencing and traffic control planning have to be coordinated to ensure safe and adequate traffic flow, and at the same time, safe and efficient work zones. Furthermore, construction sequencing must be planned to minimize disruptions to the local community—especially its business activities.

Of the nation's 576,000 bridges, >30% were reported to be deficient in one or more ways ("Status" 1995). The average investment required to repair, reconstruct, or rehabilitate these deficiencies over the next 2 decades is estimated at \$8.2 billion annually. In addition, more and more bridges are being built to meet the ever-increasing growth in travel demand. The U.S. Department of Transportation estimates an annual 2.5% growth rate in travel demand over the next 2 decades ("Status" 1993). On average, every year for the last 3 years >1,600 new urban bridge projects were executed.

This paper presents a model for evaluating the effectiveness of bridge construction plans (BCPs) during the design phase. It is intended to help designers balance BCP impacts on project performance, traffic flow, and business activity. The model was developed through observing large urban bridge construction projects in Texas and using input from design and construction experts.

First, the model scope and development methodology are summarized. Next, the final model and the details of the evaluation factors and subfactors are explained, followed by model validation. Finally, some conclusions are presented.

BCPs

A BCP is a comprehensive plan for the construction of a bridge that integrates construction sequencing and traffic control planning. Because of its impact on surrounding neighborhoods and overall project performance, it is desirable to optimize the BCP. Several individuals and organizations have conducted research to help bridge designers enhance the design and constructability of their projects [for example, Rowings et al. (1991) and McCullough and Patty (1993)]. Others developed expert systems to provide advice regarding traffic

control planning within highway construction projects [for example, Fisher and Rajan (1996)].

However, planners of urban bridges lack any objective tool for evaluating different BCP alternatives during the design phase. Developing and evaluating BCP alternatives could result in tremendous savings to the owner, contractor, and public (O'Connor and El-Diraby 2000). With the expected large public investment in bridge construction, a model for evaluating BCPs is clearly needed and could yield sizable returns.

EVALUATION MODEL SCOPE

The evaluation model set out in this paper focuses on the unique challenges of urban bridge projects. It includes parameters that are common to most bridge projects. Additional project-specific factors should be developed by each project's team based on particular project conditions.

BCP, as defined here, focuses on the construction phase of the project. Hence, the model is intended for application after the following decisions have been made:

- Selection of bridge layout (capacity, elevations, alignment, ramps, etc.)
- Selection of bridge structural system (segmental, precast, cast-in-place, etc.)

Variations in such decisions can have profound impact on BCP effectiveness and selection. An extended research effort is needed to develop a comprehensive system to incorporate all these parameters into an integrated evaluation process.

EVALUATION MODEL DEVELOPMENT

The research methodology involved three stages: development of a preliminary model, final model development, and model validation.

A preliminary evaluation model was developed through reviews of project documentation, informal interviews with design and construction engineers, and observation of three major highway projects in Texas for a period of 18 months. This version of the model included five major factors: safety *S*, accessibility *A*, carrying capacity *C*, schedule performance *T*, and budget performance *B*. An additional 27 subfactors *SF* were established to facilitate the assessment of the major factors. (These subfactors were later reduced to 22. A complete listing and discussion of the final subfactors is presented in the next section.)

The final model was developed through formal interviews with industry experts. The first part of the interview included two questions regarding the proposed factors:

- Significance: Assess the relative significance of the proposed factors/subfactors for the success of a BCP.

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- Ease of measurement: Assess the ease of measuring the proposed subfactors during the design phase.

A scale of 0–6 was used in the assessment, with 6 being the most significant or easiest to measure. Table 1 shows the scale used.

The second part of the interview was an open-ended session where the experts could speak in an unrestrained format. They were encouraged to add any factors/subfactors that were not already included on the list.

Twelve experts were interviewed during this stage. Eight of them were from the Texas Department of Transportation (TxDOT), two were from contracting firms, and two were

from engineering consulting firms. Among the 12, 5 were top managers in their respective organizations, 4 were senior design engineers, and 3 were senior construction engineers.

Fig. 1 shows the average significance score of all subfactors within each major factor. The average scores were as follows: safety subfactors, 4.4; accessibility subfactors, 4.3; carrying capacity subfactors, 5.1; BCP schedule, 5; and BCP budget, 5. The grand average score was 4.45.

Similarly, Fig. 2 shows the average ease of measurement score for all subfactors within each major factor. The majority of interviewees found it fairly easy to estimate these factors (grand average = 3.48 and median = 4). However, the designers, the intended users of the model, found it easier to do the evaluation than the managers and construction engineers. The average rating for the designers was 3.85. Managers and construction engineers average ratings were 3.23 and 3.42, respectively.

In comparing the ease of measuring major factors, interviewees ranked them as follows (based on the average rating of all subfactors): budget, 3.67; safety, 3.57; accessibility, 3.48; schedule, 3.25; and carrying capacity, 2.8. Designers provided the same ranking with mostly higher ratings than aver-

TABLE 1. First Round Interviews: Scoring Scale

Question	Score			
	0	2	4	6
Significance	No	Low	Considerable	Major
Ease of measurement	Very hard	Hard	Easy	Very easy

Note: Use numbers 1, 3, and 5 as intermediate scores between these options.

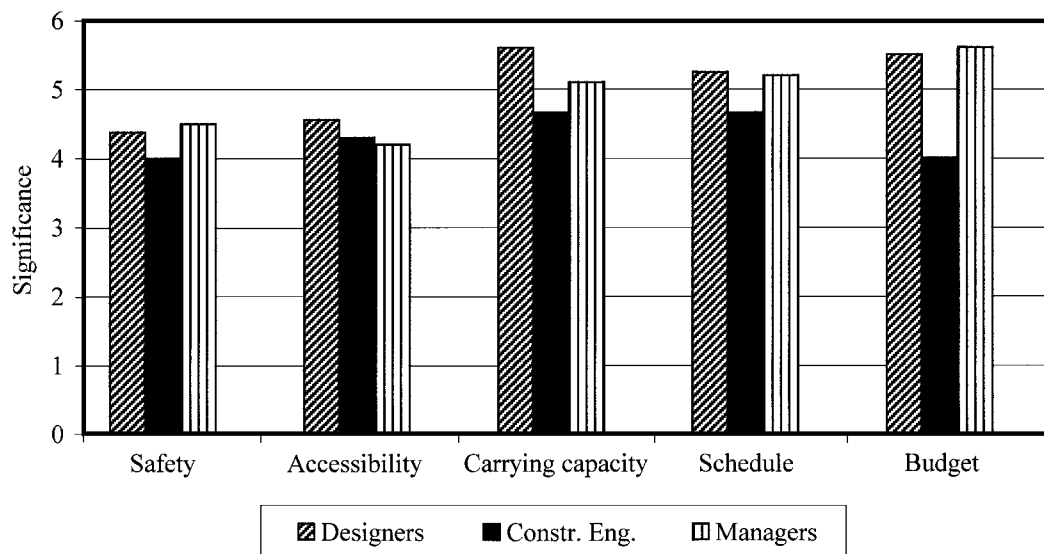


FIG. 1. Subfactor Average Significance Score

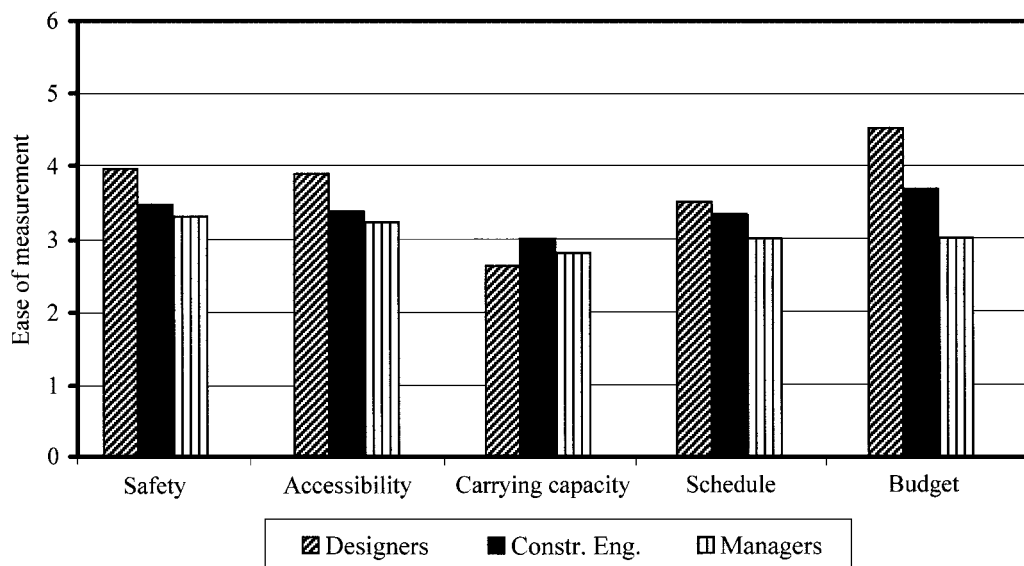


FIG. 2. Subfactor Average Ease of Measurement Score

age: budget, 4.5; safety, 4.0; accessibility, 3.9; schedule, 3.5; and carrying capacity, 2.63.

The interviewees were also asked to assess the relative significance of the major factors on the same 6-point scale. The grand average score for all major factors was 4.76, with a median of 5.

The interviewees were in agreement that safety is the most important factor (average = 5.75). The other four factors also received high ratings: accessibility, 4.58; carrying capacity, 4.58; schedule, 4.41; and budget, 4.5.

The interviewees suggested two additional major factors: bridge aesthetics and constructability. They also suggested eight additional subfactors and expressed concerns about redundancy between two pairs of subfactors.

Variations in bridge aesthetics, however, do not usually influence BCP. The aspects of constructability relevant to BCP are already included in the safety and accessibility factors; therefore, adding it would be redundant [for a full discussion, see El-Diraby and O'Connor (1999)].

Based on an analysis of significance and ease of measurement scores, and interviewees' comments, the subfactors (27 + 8) were reduced to 22. All of these 22 subfactors scored at least 3.3 in each criterion.

BCP EVALUATION MODEL

The final model includes the 5 major factors and 22 subfactors. Table 2 lists all the subfactors, while the Appendix provides a complete definition of each subfactor.

The objective matrix technique (OM) was selected to aggregate the subfactors' scores because of its simplicity and adaptability to the construction industry (Tucker and Scarlett 1986; Yoon and Hwang 1995). Furthermore, the type of aggregation technique was proven to be insignificant to the outcome of the decision-making process (Karni et al. 1990).

In OM, every subfactor is evaluated on a scale of 1–10, with 10 being the best score. The score of each major factor is the weighted sum of all its subfactors. The final score of a BCP is the weighted sum of all the scores of the major factors. For more details about OM see Riggs (1986).

Fig. 3 shows the final OM used to compare different BCPs. The equations used for calculating the final score of each BCP are presented below

BCP final score F :

$$F = w_1 \times S + w_2 \times A + w_3 \times C + w_4 \times T + w_5 \times B + w_6 \times Q \quad (1)$$

Safety score S :

$$S = \sum_{i=1}^{11} k_i \times (SF)_i \quad (2)$$

Accessibility score A :

$$A = \sum_{i=12}^{18} k_i \times (SF)_i \quad (3)$$

Carrying capacity score C :

$$C = \sum_{j=1}^m c_j \times b_j \quad (4)$$

where b = duration of each delay or blockage condition on the highway due to BCP; c = number of cars blocked or delayed under each condition; i = subfactors counter; k = subfactor relative weight; Q = score of any additional project-specific

TABLE 2. Final Major Factors and Subfactors List and Their Weights

Subfactor ^a	Weight (%)
(a) Safety 24%	
1. Overhanging equipment	9
2. Adequacy of traffic barrier	11
3. Traffic-activity interaction length	6
4. Distance between traffic and construction	8
5. Lane width	11
6. Detour length	7
7. Detour curve quality	11
8. Working on one side of traffic versus working between traffic lines	9
9. Working at high traffic volumes versus working at low traffic volume	7
10. Day shift versus night shift	9
11. Traffic change	12
(b) Accessibility 19%	
12. Reduction of number of traffic accesses	16
13. Number of forced diversions (to traffic)	15
14. Reduction of access points to businesses	16
15. Reduction in businesses parking space	13
16. Additional distance from ramp (for businesses)	12
17. Construction congestion in front of business	14
18. Contractor access to work zone	14
(c) Carrying Capacity 19%	
19. Number of cars blocked or delayed	N/A
20. Blockage/delay duration	N/A
(d) Schedule 19%	
21. Savings in time	N/A
(e) Budget 19%	
22. Savings in Cost	N/A

Note: N/A = not applicable.

^aSubfactors shown in bold face received a significance score of 4.5 or more.

	Safety	Accessibility	Carrying capacity	Schedule	Budget	Project specific factor(s)	Total
Weights	W_s	W_a	W_c	W_t	W_b	W_q	100%
BCP #1	S_1	A_1	C_1	T_1	B_1	Q_1	F_1
BCP #2	S_2	A_2	C_2	T_2	B_2	Q_2	F_2
BCP #3	S_3	A_3	C_3	T_3	B_3	Q_3	F_3
BCP #n	S_n	A_n	C_n	T_n	B_n	Q_n	F_n

FIG. 3. BCP Objective Matrix

factor(s); and w = major factor relative weights. For a full explanation of these symbols, see the Notation list.

MODEL APPLICATION PROCEDURES

The major steps of model application are as follows:

1. Develop additional evaluation factors/subfactors based on the conditions of the project.
2. Adjust relative weights to the needs of the project.

3. For each BCP alternative, evaluate all subfactors (see the example in the next section).
4. For each BCP alternative, calculate the scores of major factors.
5. Compose the OM for each BCP. Select the BCP with the highest score.

SCORING INDIVIDUAL SUBFACTORS

The development of a scoring technique for each subfactor presented a challenge to this research effort. Every subfactor has its unique measuring units. As a result, the following rule was developed to overcome the diversity of evaluating subfactors:

- Measure each subfactor in its own units (length, traffic count, area, number of times a condition occurs, dollars, time, etc.)
- Compare the different subfactors for all BCPs under study. The BCP with the best performance (regarding the subfactor under consideration) is assigned a score of 10 for this subfactor. Other BCPs are scored relative to their performance.

For example, suppose that in a bridge project the evaluation team has three BCP options (with good developed schematics for each). Suppose also that the subfactor under consideration is "adequacy of traffic barrier," which is part of the safety factor (Fig. 4). BCP No. 1 has four construction phases. Assume there are six violations of this subfactor in phase No. 1 (six times where an adequate traffic barrier was not provided), three violations in phase No. 2, no violations in phase No. 3, and three violations in phase No. 4. The total number of inadequate traffic barrier conditions in BCP No. 1 adds up to 12. Similarly, assume that BCP No. 2 has seven total violations and BCP No. 3 has five total violations.

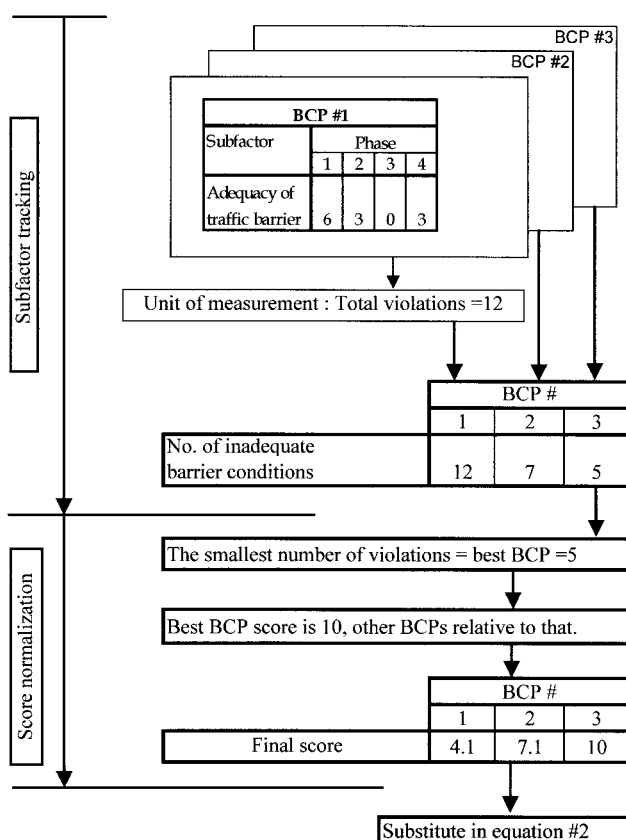


FIG. 4. Scoring Individual Subfactors—Typical Example

BCP No. 3 has the best performance (i.e., fewest violations associated with traffic barriers). BCP No. 3 is assigned a score of 10. BCP No. 1 receives a score of $(10 \times 5/12) = 4.1$, and BCP No. 2 gets a score of $(10 \times 5/7) = 7.1$. All these scores should be substituted into (2). Fig. 4 shows the procedure for calculating this example.

MODEL VALIDATION

The last stage of this research effort focused on validating the proposed model. With the design process of urban bridge projects usually extending over several years, it was not feasible to validate the proposed evaluation procedures through rigorous testing during actual project design. Therefore, it was decided to rely on two techniques: input from a second set of domain experts and actual application of the model to a single bridge planning case.

Model Validation Interviews

A total of 11 interviews were conducted during this stage. Six participants were design engineers and five were managers. Five interviews were conducted with TxDOT personnel, two with Federal Highway Administration personnel, and four with consulting firm personnel.

Because of its specific scope, this interview was designed in a strictly structured format. The interview included a set of five questions:

1. Significance: Assess the relative significance of each subfactor.
2. Generality: Can each subfactor be applicable to any bridge project? (Can each subfactor be meaningful to a generic bridge project?)
3. Data availability: Is the data required for evaluating each subfactor available or can it be estimated during the design phase?
4. Comprehensiveness: How well did the proposed factors/subfactors cover the major concerns regarding BCP effectiveness?
5. Impact: Based on your experience, would the consideration of these factors/subfactors be of benefit to BCP effectiveness?

Questions 1, 4, and 5 were scored on a scale of 0–6 with 6 presenting the best performance in each case. Table 3 shows the semantics of each score level. Questions 2 and 3 were answered on a yes/no basis for each subfactor. (The total number of answers for each question = 22 subfactors \times 11 experts = 242.)

In this round, the average significance score of all subfactors was 4.39 out of 6. None of the subfactors scored below the preset threshold significance score of 3.5, which indicates a high approval rate of the subfactors by the second validation group. Fig. 5 presents a comparison of the average significance score of each subfactor in both rounds of interviews. As seen in the figure, the two groups of experts were very close in their assessment of subfactor significance.

TABLE 3. Second Round Interviews: Scoring Scale

Question	Score			
	0	2	4	6
Significance	No	Low	Considerable	Major
Comprehensiveness	Not at all	Minimal	Good	Very good
Impact	None	Low	Considerable	Major

Note: Use numbers 1, 3, and 5 as intermediate scores between these options.

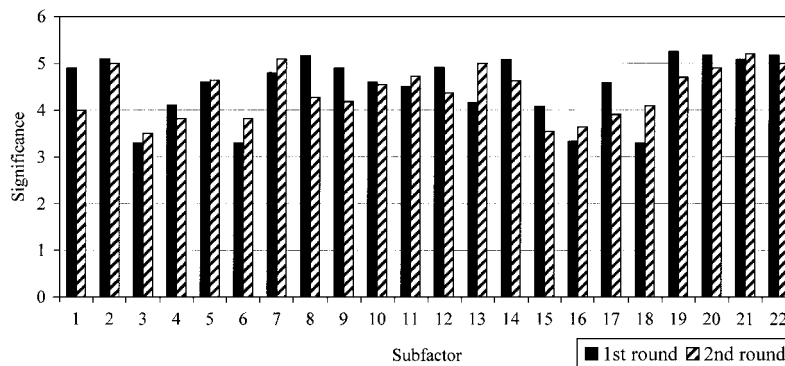


FIG. 5. Comparison of Significance Score in Both Rounds of Interviews

About 93% of all responses to the second question (model generality) and about 97% of all responses to the third question (data availability) were positive. No single subfactor in either question received a negative score from more than one expert.

The average score for the fourth question (comprehensiveness) was 5 out of 6. As to the last question (impact of model on future BCP development), the experts were optimistic: the average response was 4.7 out of 6.

This round of interviews indicated a high level of satisfaction among experts regarding the model and its application, and that the proposed factors cover the majority of concerns that are meaningful in achieving an optimal BCP.

Model Application

The model was then applied to the case of Mockingbird Bridge in Dallas, Tex. This bridge project was a very good opportunity for model application, because it presented a typical urban bridge project with two different BCPs. More importantly, the TxDOT was conducting an independent evaluation of both BCPs.

The original BCP was designed by a large consulting firm. It was composed of 16 steps and required a total of 22 traffic shifts (16 diversions for the expressway traffic and another 6 diversions for Mockingbird Bridge traffic). The owner and contractor thought that this BCP was too complex. As a result, the owner commissioned a study to develop a new BCP. The new BCP included 11 steps and required only nine traffic shifts (six for the expressway and three for the Mockingbird Bridge traffic). The new BCP saved about 15% of the project's direct cost and 30% of its estimated duration.

The model presented here was used to evaluate the two BCP alternatives. The evaluation process consumed 42 man-hours (including participation of TxDOT personnel). Fig. 6 shows the final OM for the Mockingbird Bridge case. BCP No. 1 (old plan) scored 7.4 out of 10, and BCP No. 2 (new plan) scored 9.7.

Later, the TxDOT management, the TxDOT safety committee, and community and contractor representatives adopted the new BCP for execution—which confirmed the model application results.

The new BCP outperformed the original BCP in schedule and budget performance factors. More importantly, this was achieved while enhancing safety, accessibility, and carrying capacity. The new plan achieved this through careful analysis and integration of construction sequencing and traffic control planning. (For more details, see O'Connor and El-Diraby 2000.)

This case demonstrates the benefits and need for BCP evaluation, to balance the usually conflicting objectives of BCP. Through model application, enhanced performance in the project schedule and budget did not overshadow other equally

	Safety	Accessibility	Carrying capacity	Schedule	Budget	Total
Weights	24	19	19	19	19	100%
BCP #1	8	7.5	6.2	6.6	8.3	7.4
BCP#2	9.3	9.2	10	10	10	9.7

FIG. 6. Mockingbird Bridge Case Objective Matrix

important factors (safety, accessibility, and carrying capacity). The model, therefore, enables the decision maker to gauge the relative performance of BCP alternatives respective to the five major factors.

FACTOR RELATIVE WEIGHTS

The relative weights of the five major factors are as follows (based on the experts' response to the significance question in both rounds):

- Safety: 24%
- Accessibility: 19%
- Carrying capacity: 19%
- Schedule performance: 19%
- Budget performance: 19%

The relative weights of subfactors within each major factor came out to be almost evenly distributed (Table 2).

The 23 experts who participated in model development, although living in Texas, had worked in 31 different states over their careers. Their input would be a very good starting point in weight assessment. However, these weights should not be considered universal because every project has its unique conditions. Several facts should guide the final allocation of weights—for example, available right-of-way, complexity of design, traffic volume, level of business activity around the project, and community input regarding preferences to construction-access trade-off.

CONCLUSIONS

This paper presents a model for evaluating BCPs during the design phase. The model employs five major factors: safety, accessibility, carrying capacity, schedule performance, and budget performance. An additional 22 subfactors are identified to facilitate the evaluation of these major factors.

Input from industry experts and actual application of the model indicate the following:

- The proposed model is applicable to most bridge projects.
- The model is fairly easy to apply.
- The model covers the majority of concerns associated with bridge projects.
- The data needed for model application are available during the design phase.
- There is a strong belief that the implementation of the model could have a positive impact on BCP development.

APPENDIX. SUBFACTOR LIST

Safety Factor

This evaluation factor is proposed for measuring the level of safety a BCP can provide to both the traveling public and the construction crew, above and beyond the minimum standards. It includes the following subfactors:

1. Overhanging equipment: Relates to situations in which construction equipment is overhanging or swinging over traffic
2. Adequacy of traffic barrier: Deals with how well the traffic barrier separates traffic and construction
3. Traffic-activity interaction length: Refers to the length of construction zone adjacent to traffic
4. Distance between traffic and construction activity: Refers to the cross distance between traffic and construction zone
5. Lane width: Refers to the average lane width of the freeway and frontage road during construction
6. Detour length: Measures total detours required to accommodate the construction
7. Detour curve quality: Measures the sharpness of horizontal and vertical curves (a special table of horizontal and vertical curve degrees was established to score this subfactor)
8. Working on one side of traffic versus working between traffic lines: Refers to the location of the crew relative to traffic (working between traffic lines is the more dangerous situation)
9. Working at high traffic volume versus working at low traffic volume: Deals with the intensity of traffic around a construction zone (a crew working at high traffic volumes is in a more dangerous situation than a crew working at low volumes)
10. Day shift versus night shift: Deals with crew visibility to traffic (night shifts are more dangerous than day shifts)
11. Traffic changes: Deals with the changes to traffic path (it includes changes such as lane drop, detours, and traffic diversion and also differentiates between changes to highway, frontage road, and secondary roads)

Accessibility Factor

This evaluation factor is proposed for assessing the BCP's effect on traffic, business, and contractor accessibility during construction. It includes the following subfactors:

12. Reduction of number of traffic accesses: Frequency of closing highway on/off ramps
13. Number of forced traffic diversions: Deals with forced diversions for traffic, such as diverting traffic to another road
14. Reduction of access points to businesses: Frequency of closing/impeding access to businesses

15. Reduction of parking space: Refers to the reduction in business parking spaces caused by construction work
16. Additional distance from ramp (for businesses): Evaluates the impact of changing ramp locations on business activity
17. Construction congestion in front of business: Deals with the level of work around the business that may impede access to a business (a checklist was established to help designers assess this subfactor)
18. Contractor access to work zone: Refers to the availability of access to contractor equipment such as cranes or hauling equipment (a checklist was established to help designers assess this subfactor)

Carrying Capacity Factor

This factor evaluates BCP impact on the carrying capacity of the freeway. A BCP usually requires closing portions of the freeway, which results in more congestion on other city highways as well as increased user cost. The sum of the products of the following two subfactors is used to evaluate the carrying capacity performance for each BCP:

19. Number of cars blocked/delayed: The estimated number of cars blocked or delayed on the highway when such delay is caused by construction
20. Blockage/delay duration: Estimated duration of each blockage/delay condition

Schedule Performance Factor

This factor evaluates the effectiveness of a BCP's schedule. It is measured by

21. Percentage savings in schedule

Budget Performance Factor

This factor evaluates the effectiveness of a BCP's budget. It is measured by

22. Percentage savings in cost

REFERENCES

- El-Diraby, T. E., and O'Connor, J. T. (1999). "System for evaluating bridge construction plans." *Res. Rep.*, Ctr. for Transp. Res., University of Texas, Austin, Tex.
- Fisher, D. J., and Rajan, N. (1996). "Automated constructability analysis of work-zone traffic-control planning." *J. Constr. Engrg. and Mgmt.*, ASCE, 122(1), 36–43.
- Karni, R., Sanchez, P., and Rao Tummala, V. M. (1990). "A comparative study of the multi-attribute decision making methodologies." *Theory and decision*, 29(3), 203–222.
- McCullough, B. G., and Patty, R. (1993). "An INDOT lessons learned constructability program and integrated multi-media system." *Res. Proj. C-36-6711*, Purdue University, West Lafayette, Ind.
- O'Connor, J. T., and El-Diraby, T. E. (2000). "Urban freeway bridge construction planning: Case of Mockingbird Bridge." *J. Constr. Engrg. and Mgmt.*, ASCE, 126(1), 61–67.
- Riggs, J. L. (1985). "What's the score?" *The Military Engr.*, 77(503), 496–499.
- Rowings, J. E., Harmelink, D. J., and Buttler, L. D. (1991). "Constructability in the bridge design process." *Res. Proj. 3193*, Iowa State University, Ames, Iowa.
- "Status of the nation's highways and bridges: Conditions and performance." (1993). *Rep. of the Secy. of Transp. to the U.S. Congr. Pursuant to Sect. 307, Title 23*, Washington, D.C.
- "Status of the nation's surface transportation system: Conditions and performance." (1995). *Rep. of the Secy. of Transp. to the U.S. Congr. Pursuant to Sect. 307, Title 23*, Washington, D.C.
- Tucker, R. L., and Scarlett, B. R. (1986). "Evaluation of design effectiveness." *Source Document 16*, Construction Industry Institute, Austin, Tex.

NOTATION

The following symbols are used in this paper:

A = accessibility factor score;
 B = budget performance factor score;
 b = duration of each delay or blockage condition on highway due to BCP;
 C = carrying capacity factor score;
 c = number of cars blocked or delayed in each condition;

F = final BCP score;
 k = subfactor relative weight;
 Q = score of any additional project-specific factor(s);
 S = safety factor score;
 SF = generic symbol for subfactors;
 T = schedule performance factor score; and
 w = major factor relative weight.

Subscripts

i = subfactor counter;
 j = blockage conditions counter; and
 m = total number of blockage conditions in BCP.