

Article

Multi-Criteria Evaluation Framework in Selection of Accelerated Bridge Construction (ABC) Method

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Abstract: Accelerated Bridge Construction (ABC) is bridge construction that uses innovative planning, design and construction methods in a safe and cost-effective manner, which reduces construction mobility and environmental impacts, and contributes to city sustainable planning and development. To deal with the pressing need to support the decisions associated with the selection between the ABC and conventional bridge construction, this paper presents the development of a multi-criteria evaluation framework. Methods are developed and identified to estimate the construction, agency, and user costs associated with the construction methods. A novel model was developed to allow the estimation of the construction and agency costs of ABC relative to conventional construction. This paper also demonstrates the estimation of user costs, including those associated with mobility, reliability, safety, and emissions, utilizing combinations of the proposed prediction method. The paper then compares the use of the return-on-investment and Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) Multi-Criteria Decision Making (MCDM) evaluation approaches in the decision to select between ABC and conventional bridge construction. The results from the employment of the two approaches to a case study demonstrate the advantage of using the TOPSIS approach, which is also applicable in the urban planning process.

Keywords: Accelerated Bridge Construction; construction cost; road user cost; return-on-investment analysis; Multi-Criteria Decision Making; Fuzzy TOPSIS

1. Introduction

According to the United States Department of Transportation (USDOT), 25.9% of all the bridges in the United States are either structurally deficient or functionally obsolete. There is therefore a pressing need for significant bridge repair and replacement efforts [1]. These bridge projects create a challenge to State Transportation Agencies (STAs) to minimize the associated costs and impacts on traffic, associated with the construction. In an effort to combat this challenge, the Federal Highway Administration (FHWA) is adopting and promoting the implementation of accelerated bridge construction techniques (ABC) through the “Every Day Counts” initiative to expedite project delivery and minimize their impacts on the transportation network [2].

Accordingly, a number of STAs are implementing ABC techniques and have experienced positive outcomes in a significant number of bridge replacement and/or rehabilitation projects. However, ABC techniques are often associated with high initial costs, which deter many STAs from a wider implementation of these techniques [3]. Therefore, there is a pressing need to provide decision makers with the appropriate tools to support the decisions associated with ABC versus conventional bridge construction including: construction costs, agency cost, and user costs. This paper presents a

framework for analyzing and estimating the ABC impacts, compares them to those of conventional construction methods, and utilizes the results in decision-making processes. The aim is to support agency decisions when selecting between conventional and ABC bridge construction approaches. The paper explores the methods for the estimation of construction, agency, and user costs and uses the results from the estimation as inputs to a return on investment (present-worth) analysis and a Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) Multi-Criteria Decision Making (MCDM) analysis. The decision recommendations based on these two analysis approaches are compared for a real-world case study.

2. Literature Review

Assessing the total costs associated with ABC versus conventional bridge construction methods requires the evaluation of construction costs, engineering and inspection costs, user costs, ecological costs, revenue loss costs, right of way, quality of work, and the impact on surrounding communities and businesses [4].

Qualitative decision support tools are simple in application while there are only a few evaluation criteria. One of the qualitative tools is the FHWA flowchart that is designed to assist decision makers in determining the use of prefabricated bridges concerning the construction schedule, location, safety and traffic impacts [5]. On the other hand, quantitative method, such as life-cycle cost analysis (LCCA), is also used in bridge construction projects. Kendall et al. developed a life-cycle costs analysis model to compare alternative bridge deck designs from a sustainability perspective that accounts for agency, user, and environmental costs [6]. The results show that the mobility costs related to construction compromise 90% of the total costs. In the research from Safi et al., the life-cycle considerations are incorporated into bridge investment and management decision-making processes with optimizing the use of taxpayers' money [7]. Antunes et al. developed the life-cycle costs assessment tool for pavement structure alternatives concerning the technical, economic and environmental factors [8]. The proposed tool was simple and useful to select the ideal paving solutions in the case study. However, more and more factors, that are difficult to quantify, need to be considered in the decision-making process, which makes the employment of LCCA restricted.

To deal with the complex decision-making process in bridge construction projects, the Multi-Criteria Decision-Making (MCDM) approach involving both qualitative and quantitative factors was widely used. A variety of MCDM methods and techniques, including AHP (Analytic Hierarchy Process), SAW (Simple Additive Weighting), COPRAS (COMplex PROportional ASsessment), TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) and so on, were employed in the decision-making practice [9]. Among them, the analytic hierarchy process (AHP) is one of the most popular MCDM method. Youssef et al. developed an intelligent Decision Support System based on the AHP method that helps construction professionals and designers during the early stages of a construction project [10]. The research found that the bridge physical characteristics and stake holders' objectives could also affect final evaluation. In the research from [11–14], the decision-making systems to determine the weights of both qualitative and quantitative factors, such as environmental, economic and social aspects, was built based on the AHP method. The case studies illustrated the capability of the AHP method in the decision-making process. Nevertheless, in order to make the AHP method more flexible, the integrated AHP method was also developed and implemented. According to the maintenance priorities, Wang et al. proposed an integrated AHP–DEA methodology for bridge risks assessment of different bridge structures [15]. The new method was able to deal with any number of criteria. Aghdaie et al. explored to prioritize the construction projects of footbridge, considering the total cost, environmental factors, and socio-economic factors using integrated AHP and COPRAS-G methods [16]. Bitarafan et al. proposed an integrated MCDM approach based on the SWARA and WASPAS methods to evaluate the real-time intelligent sensors for monitoring the structural health of bridges [17]. The evaluation criteria were obtained through an expert survey. Ardeshtir et al. developed a hybrid decision-making method based on the Geographic Information System (GIS) and

AHP methods and applied it to bridge construction site selection [18]. Moreover, in order to handle the uncertainty of subjective judgement, the fuzzy AHP method was developed to select the bridge construction method [19]. The fuzzy triangular number was proposed to solve the uncertainty and vagueness, and the results present the capability of the new approach.

Another popular MCDM method is the Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) method. TOPSIS was first developed by Hwang and Yoon [20] and is based on the concept that the chosen alternative should have the shortest distance from the positive ideal solution (PIS) and the farthest from the negative ideal solution (NIS). Zavadskas et al. reviewed the papers which developed, extended, proposed and presented TOPSIS approach for solving decision-making (DM) problems [21]. The conclusions present the wide use of TOPSIS method in business, engineering and other fields. Kannan et al. proposed a framework using Fuzzy TOPSIS to select green suppliers for a Brazilian electronics company [22]. The framework is built on the criteria of green supply chain management (GSCM) practices. Guo et al. employed the fuzzy TOPSIS method to select the Electric Vehicles site from a sustainability perspective, which consists of environmental, economic and social criteria [23]. A sensitivity analysis indicates that the selection of the alternative is no matter with the sub-criteria weight change. Selim et al. developed a maintenance planning framework to reduce and stabilize the maintenance costs of the manufacturing companies [24]. The framework is based on fuzzy TOPSIS and failure mode and effects analysis (FMEA) techniques and supports maintenance planning decisions in a dynamic way. For the decision-making process in construction projects, there are also several papers to explore the TOPSIS or integrated TOPSIS method. Wang et al. developed a fuzzy TOPSIS method based on alpha level sets and nonlinear programming, and its application in bridge risk assessment [25]. The results illustrate the better performance of using the fuzzy TOPSIS method. Taylan et al. proposed a fuzzy TOPSIS and AHP framework for construction projects selection and risk assessment considering time, cost, quality, safety and environment sustainability [26]. To deal with the imprecise or vague nature of complex decisions, Chaphalkar et al. deployed the fuzzy AHP and TOPSIS approach in the selection of bridge type in Pune city, respectively [27]. Both the AHP and TOPSIS methods suggested the same alternative. However, the TOPSIS method was simpler for use and robust in assessing more criteria than the AHP method.

As a summary, a variety of methods were developed and implemented to deal with the decision-making problem in construction projects. The LCCA method is applicable to assess the factors that can be quantified, while the AHP method is able to handle the decision-making problem with a few criteria. Nevertheless, in order to account for the imprecise or vague nature of complex decisions, the TOPSIS method is more applicable and flexible.

3. Methodology

In this paper, a framework was developed and employed to estimate the components of the total cost of ABC versus conventional construction methods, and to use these estimates as inputs to return-on-investment (present-worth) and TOPSIS MCDM analyses. The following sections describe the methods developed.

3.1. Construction Costs

Construction costs include the material, labor, and equipment costs needed to build the bridge, in addition to the contractor's costs. Agencies still have no good answers regarding the relative costs of the two construction approaches. To help answering this question, a model was developed in this study to estimate and identify the expected construction costs expressed in \$/ft² for ABC bridges.

To develop the cost estimation model, historical data on construction costs of ABC projects was collected from the FHWA SharePoint database developed under the National ABC Project Exchange, which is an ongoing project sponsored by Florida International University—University Transportation Center. This database includes detailed information about a considerable number of nationwide ABC projects; including, but not limited to: construction schedule, type of structure, cost, and the

ABC methods used. The cost data in the database includes the engineer's estimate, bid, and final costs. The final construction cost is given per square foot and in some cases a comparison of the construction cost per square foot for the same bridge, if it was constructed conventionally, is given, which enabled the research team to conduct a comparative analysis between the costs of the two methods. Furthermore, follow-up emails and phone calls to transportation agency personnel was conducted to collect any missing data, where needed. In total, the research team was able to collect sufficient data for 65 ABC projects from 29 different states (as shown in Figure 1). The collected data cover bridges constructed between the years of 1998 and 2013 include ABC methods such as: self-propelled modular transporter (SPMT), lateral sliding, and pre-fabricated bridge elements & systems (PBES).

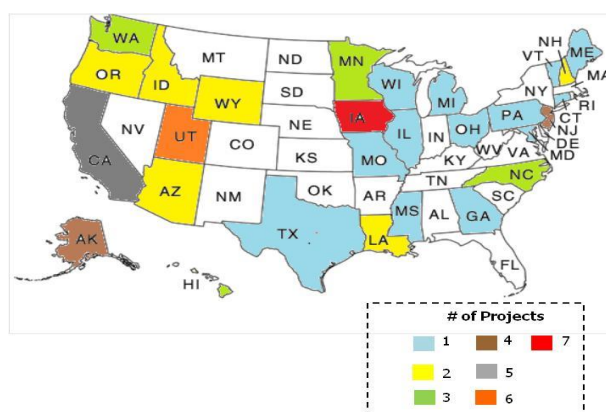


Figure 1. Data from Nationwide ABC Projects.

The collected cost data was normalized by time and location to allow for an accurate analysis. This normalization was performed using the time and location indices from the widely used RSMeans cost data [28]. All construction costs were adjusted to the year 2014. Similarly, construction costs were normalized to the national average using the indices correspondent to bridge locations. The data was grouped by four main variables: (i) bridge location, (ii) type (concrete/steel), (iii) annual average daily traffic (AADT), and (iv) number of spans. For example, 39 out of the 65 bridges were constructed in rural locations and 50 of them were concrete bridges (see Figure 2). The 65 bridges had spans ranging from a single span to seven spans, and the length of span ranges from 60 ft to 200 ft. The annual average daily traffic on these bridges ranges from, as low as few hundreds, to as high as 200,000 vehicles per day.

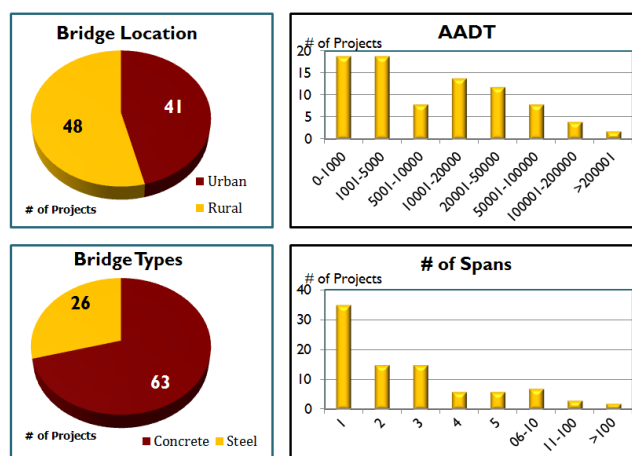


Figure 2. Descriptive Statistics of the Collected Construction Cost Data.

A classification and regression tree (C&RT) analysis was performed on the abovementioned grouped data using the Statistical Package for the Social Sciences (SPSS) software package. As shown in Table 1, the C&RT analysis showed that all of the aforementioned four characteristics had significant impacts on the final total construction cost of the ABC bridges with the AADT and number of bridge spans being the two factors with the highest impacts. The analysis shows that the prediction of the final cost per square foot of an ABC bridge improves considerably after categorizing the data by the number of spans and the AADT.

Table 1. Relative Importance of Each Variable According to the C&RT Analysis Results.

Independent Variable	Importance
AADT	100.0%
Number of Span	99.2%
Type	59.4%
Location	35.3%

The aforementioned four independent variables were used to develop a model to estimate the range of construction costs per square foot for an ABC project using logit regression analyses. The AADT values used as independent variables in the model were divided into eight different intervals, each given a categorical value as shown in Table 2. The bridge type was categorized as: “0” for concrete bridges casted on site, “1” for concrete bridges pre-casted and “2” for steel bridges. A value of “0” was used for bridges in rural areas and “1” for urban areas. The construction cost was also categorized as shown in Table 3.

Table 2. The AADT Independent Variable Representation.

AADT Categorical Value	AADT Range
0	0 to 1000
1	1001 to 5000
2	5001 to 10,000
3	10,001 to 20,000
4	20,001 to 50,000
5	50,001 to 100,000
6	100,001 to 200,000
7	More than 200,001

Table 3. The Cost Ranges Utilized in the Analysis.

Category	1	2	3	4	5	6	7	8	9	10
Range (\$/ft ²)	0–100	101–200	201–300	301–400	401–500	501–600	601–700	701–800	801–900	901–1000

It is noteworthy that the predicted cost represents a national average due to the cost data normalization mentioned earlier and it is therefore important to adjust it to the specific location of the bridge under study. The RSMeans cost indices mentioned above can be used for this purpose [28]. To allow for comparing the predicted cost with the conventional construction methods, the average conventional bridge construction rates published by different state departments of transportation (DOTs), were summarized and used.

3.2. Other Agency Costs

An analysis of 10 projects from ODOT was used to identify any statistically significant difference in agency costs between ABC and conventional bridge construction methods. The considered costs in this category included preliminary engineering, right of way, construction engineering, and inspection costs. Due to limited data availability, statistical data analysis was performed only for preliminary

engineering and construction engineering costs both of which did not show any statistically significant difference between ABC and conventional methods. The examined data seems to indicate that the agency cost can be approximately calculated as 20% of the construction cost for both conventional and accelerated bridge construction.

3.3. User Costs

A report by the FHWA presents a framework for the use of user and construction costs in construction alternative analysis [29]. The report also discusses how the unit cost of delays, vehicle operating cost, crashes, and safety can be calculated based on outputs from tools and methods that can calculate these parameters.

A number of tools have been developed that can be used to assess the impacts of construction on mobility. The FHWA Traffic Analysis Toolbox documents [30] classify these tools to sketch planning tools, traffic demand models, signal optimization tools, macroscopic simulation, mesoscopic simulation, and microscopic simulation. These documents provide guidance to assist in selecting between these different types of tools based on various factors. The sketch planning tools range from simple spreadsheets that allow the analysis of a single link like the Q-DAT [31] developed for Texas Transportation Institute (TTI) to slightly more complicated tools like the QuickZone tool [32] developed by the FHWA that allows the modeling of multiple links on the subject facility and an alternative route. A good example of a macroscopic simulation model is the tool that implements the freeway and urban street facility procedures of the Highway Capacity Manual (HCM) including the updated work zone procedures in the latest version of the HCM [33]. An example of the use of simulation-based dynamic traffic assignment modeling tools is the WISE approach developed as part of a Strategic Highway Research Program 2 (SHRP 2) project [34]. However, the existing research does not address comprehensively the tools and methods to perform the assessments of user costs.

In this paper [35], mobility, reliability, safety and emission impacts, in line with the FHWA report and SHRP 2 reliability program recommendations, are considered and assessed to estimate road user costs. For mobility impacts, the QuickZone tool was used in this study to estimate the total delay due to work zones. The mobility costs could be estimated by the equation 1 as follows,

$$\text{MobilityCosts} = \text{VOT} \times \text{TotalDelay} \times \text{Vehicle Occupancy} \quad (1)$$

where, VOT is value of time, TotalDelay represents the total delay during construction, and delay occupancy is a region-specific parameter that can vary by time of day and trip purpose (occupancy of 1.4 persons per vehicle is used in this study). The value of time (VOT) used in this study is 16.64 \$/person-hour according to the recommendation of the FHWA report mentioned earlier [29].

Another important component for road user cost is travel reliability [36]. Regression equations to estimate reliability, originally developed in the SHRP 2 L03 project [37] and later implemented in a spreadsheet tool developed in the SHRP 2 L07 project [38], were used to estimate reliability in this study, considering the lane hour lost due to construction. The utilized measures of reliability that can be calculated using the models are the nth percentile travel time indexes (TTIs), where nth could be the 10th, 50th, 80th, 95th, and mean travel time index (TTI). The TTI estimation models have the following general functional form,

$$TTI_{n\%} = e^{(j_n LHL + k_n dc_{crit} + l_n R_{0.05'})} \quad (2)$$

where $TTI_{n\%}$ is nth percentile of TTI; LHL represents lane hour lost due to incidents and/or construction; dc_{crit} is the critical demand to capacity ratio; $R_{0.05'}$ is the number of hours of rainfall exceeding 0.05 inch; and j_n, k_n, l_n represents coefficients for the nth percentile of TTI.

In this paper, the buffer time, representing the extra time budgeted for travel, is selected as the reliability measure to estimate reliability costs with the value of reliability (VOR) of 22.5\$/h based on the recommendation from SHRP 2 L04 project [39], as equations 3–4 illustrate.

$$ReliabilityCosts = VOR * BufferTime \quad (3)$$

$$BufferTime = Vehicles \times Occupancy \times AveTravelTime \times \frac{(95\%TTI - 50\%TTI)}{50\%TTI} \quad (4)$$

This paper estimates the safety impacts of work zones utilizing the default values used in the Florida ITS Evaluation (FITSEVAL) tool [40]. The average cost per crash was assumed to be 9700 dollars for property damage only (PDO) crash, 125,200 dollars for injury crash and 5,277,700 dollars for fatal crash [41], as equation 5 shows,

$$CrashCost = VMT \times CrashRate^{normal} \times CMF \times UnitCost \quad (5)$$

The average speed approach of the Motor Vehicle Emission Simulator (MOVES), developed by the United States Environmental Protection Agency (EPA) was used in this study to estimate emission [42]. The average speed approach is the simplest of the project level analysis in MOVES and is based on the average speed of the vehicles and the vehicle miles traveled by vehicle type. The utilized unit costs of emission were obtained from the FHWA report mentioned earlier [29]. Three types of pollutants are considered in this study, including Carbon Oxide (CO), Nitrogen Oxide (NOx), and Hydrocarbons (HC), as following equation describes,

$$EmissionCost = UnitCost \times VMT \times EmissionRate(PollutantType, Speed) \quad (6)$$

3.4. TOPSIS Approach to the Accelerated Bridge Construction (ABC) Decision

In this paper, five criteria including construction costs, mobility, safety, reliability, and emission impacts were considered in the evaluation. This allows direct comparison of the results of the MCDM with those of the return on investment analysis that includes the same factors. Additional factors can be included such as whether bridge location is on an evacuation route, schedule constraints, site constraints, impacts on business, impacts on freight, customer service, and so on, as considered by the FHWA flow chart and ODOT tool approaches [5].

The detailed procedures of fuzzy TOPSIS algorithm utilized in the paper can be expressed as follows,

Step 1: Construct a decision matrix. Assume there are m alternatives $A_i (i = 1, 2, \dots, m)$ to be assessed with n criteria $C_j (j = 1, 2, \dots, n)$. The decision group has K members. Let $\widetilde{w}_j^k$ to present the fuzzy importance weight of j th criterion assessed by the k th decision maker; let $\widetilde{x}_{ij}^k$ to present the rating of the A_i with respect to criterion C_j evaluated by k th decision maker. The decision matrix can be expressed as, $C_1 \dots C_n$

$$D^k = \begin{matrix} A_1 \\ \vdots \\ A_m \end{matrix} \begin{bmatrix} \widetilde{x}_{11}^k & \cdots & \widetilde{x}_{1n}^k \\ \vdots & \ddots & \vdots \\ \widetilde{x}_{m1}^k & \cdots & \widetilde{x}_{mn}^k \end{bmatrix} \quad (7)$$

$$W^k = \left(\widetilde{w}_1^k \quad \dots \quad \widetilde{w}_n^k \right) \quad (8)$$

where, $\widetilde{x}_{ij}^k$ and $\widetilde{w}_j^k$ are linguistic variables. These linguistic variables can be described by triangular fuzzy numbers.

Step 2: Calculate the integrated weight $\tilde{w}_j$ for criteria C_j and the aggregated fuzzy rating $\tilde{x}_{ij}$ of Alternative A_i under criteria C_j .

$$\tilde{x}_{ij} = \frac{1}{K} [\tilde{x}_{ij}^1 \oplus \dots \oplus \tilde{x}_{ij}^K] \quad (9)$$

$$\tilde{w}_j = \frac{1}{K} [\tilde{w}_j^1 \oplus \dots \oplus \tilde{w}_j^K] \quad (10)$$

where, $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij})$ and $\tilde{w}_j = (e_j, f_j, g_j)$ represent the fuzzy triangular number.

Step 3: Normalize the fuzzy decision matrix $\tilde{R} = [\tilde{r}_{ij}]_{m \times n}$. Let B denote the set of benefit criteria, while C is the set of cost criteria.

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*} \right), \quad c_j^* = \max\{c_{ij}\}, \quad j \in B \quad (11)$$

$$\tilde{r}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}} \right), \quad a_j^- = \min\{a_{ij}\}, \quad j \in C \quad (12)$$

Step 4: Construct the weight normalized fuzzy decision matrix $\tilde{V} = [\tilde{v}_{ij}]_{m \times n}$. $\tilde{v}_{ij}$ is the normalized fuzzy number and belongs to $[0, 1]$.

$$\tilde{v}_{ij} = \tilde{r}_{ij} \otimes \tilde{w}_j \quad (13)$$

Step 5: Calculate the distance to fuzzy positive ideal solution (FPIS) and fuzzy negative ideal solution (FNIS). Compute the closeness coefficient (CC) of each alternative.

$$d_i^+ = \sum_{j=1}^n d(\tilde{v}_{ij}, \tilde{v}_j^+), \quad i = 1, \dots, m; j = 1, \dots, n \quad (14)$$

$$d_i^- = \sum_{j=1}^n d(\tilde{v}_{ij}, \tilde{v}_j^-), \quad i = 1, \dots, m; j = 1, \dots, n \quad (15)$$

$$CC_i = \frac{d_i^-}{d_i^+ + d_i^-} \quad (13)$$

where, $\tilde{v}_j^+ = (1, 1, 1)$ and $\tilde{v}_j^- = (0, 0, 0)$.

With the TOPSIS procedures described above, the triangular fuzzy number is utilized to express the importance of each criteria and the assessment of each alternative, as Figure 3 shows. The decision-makers could use linguistic variables to express their perceptions about the level of importance of each criterion as shown in Figure 3a. The importance ranges from “very low” to “very high.” The decision-makers also provide a rating of the assessed performance of each alternative with respect to each criterion. The linguistic variable for the assessment of each alternative ranges from “very poor” to “very good,” as shown in Figure 3b.

To test the use of the TOPSIS method, four engineers with significant past experience on the subject were asked to assess the importance of each criterion and to rate the assessed performance. The responses are shown in Tables 4 and 5. To help understand the information presented in Table 5, we point as an example that the information presented in the table indicates the Expert 2 rates the ABC mobility impact as good, if the ABC produces 30% to 40% less delay compared to conventional construction.

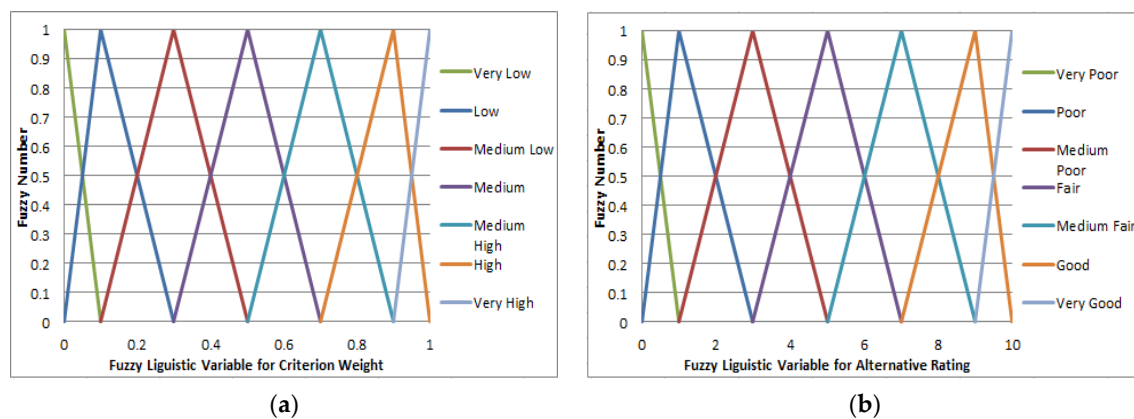


Figure 3. Fuzzy Linguistic Variable Utilized in This Study: (a) Importance of Criteria; (b) Rating of Alternative Performance.

Table 4. Criteria Importance Table.

Criteria	Expert1	Expert2	Expert3	Expert4
C1: Mobility	H	VH	VH	H
C2: Reliability	H	VH	MH	ML
C3: Safety	VH	VH	H	H
C4: Emission	M	MH	MH	L
C5: Construction Costs	VH	H	H	VH

Table 5. Rating of the Performance of ABC with Respect to Conventional Construction.

Rating	Expert	Mobility Impacts	Reliability Impacts	Safety Impacts	Emission Impacts	Construction Costs
VP	Expert1	Equal or higher	Equal or higher	Equal or higher	Equal or higher	100% higher
	Expert2	Equal or higher	Equal or higher	Equal or higher	Equal or higher	10% higher
	Expert3	10% lower	10% lower	10% lower	10% lower	50% higher
	Expert4	10% higher	10% higher	10% higher	10% higher	30% higher
P	Expert1	10~30% lower	10~30% lower	10~30% lower	10~30% lower	75~100% higher
	Expert2	0~10% lower	0~10% lower	0~10% lower	0~10% lower	5~10% higher
	Expert3	10~20% lower	10~20% lower	10~20% lower	10~20% lower	40~50% higher
	Expert4	0~10% higher	0~10% higher	0~10% higher	0~10% higher	25~30% higher
MP	Expert1	30~45% lower	30~45% lower	30~45% lower	30~45% lower	50~75% higher
	Expert2	10~15% lower	10~15% lower	10~15% lower	10~15% lower	0~5% higher
	Expert3	20~35% lower	20~35% lower	20~35% lower	20~35% lower	35~40% higher
	Expert4	0~15% lower	0~15% lower	0~15% lower	0~15% lower	20~25% higher
F	Expert1	45~60% lower	45~60% lower	45~60% lower	45~60% lower	30~50% higher
	Expert2	15~20% lower	15~20% lower	15~20% lower	15~20% lower	Equal
	Expert3	35~50% lower	35~50% lower	35~50% lower	35~50% lower	30~35% higher
	Expert4	15~30% lower	15~30% lower	15~30% lower	15~30% lower	15~20% higher
MF	Expert1	60~80% lower	60~80% lower	60~80% lower	60~80% lower	20~30% higher
	Expert2	20~30% lower	20~30% lower	20~30% lower	20~30% lower	0~5% lower
	Expert3	50~65% lower	50~65% lower	50~65% lower	50~65% lower	20~30% higher
	Expert4	30~45% lower	30~45% lower	30~45% lower	30~45% lower	10~15% higher
G	Expert1	80~95% lower	80~95% lower	80~95% lower	80~95% lower	Equal
	Expert2	30~40% lower	30~40% lower	30~40% lower	30~40% lower	5~10% lower
	Expert3	65~80% lower	65~80% lower	65~80% lower	65~80% lower	10~20% higher
	Expert4	45~60% lower	45~60% lower	45~60% lower	45~60% lower	5~10% higher
VG	Expert1	95% lower	95% lower	95% lower	95% lower	0~20% lower
	Expert2	40% lower	40% lower	40% lower	40% lower	10% lower
	Expert3	80% lower	80% lower	80% lower	80% lower	10% higher
	Expert4	60% lower	60% lower	60% lower	60% lower	5% higher

4. Case Study

A case study was used to illustrate the use of the framework developed in this study for the estimation of the direct construction costs, agency costs and user costs of bridge construction with ABC and conventional methods, and the use of the results as part of the return-on-investment and

TOPSIS MCDM approaches. The bridge is located at the interchange of I-4 and Graves Avenue in Orlando, FL (see Figure 4).



Figure 4. Location of Bridge Construction Project.

The existing two-lane four-span prestressed concrete beam bridge was 215 ft long and 30 ft wide. The replacement bridge has two 12-ft-wide traffic lanes, and a 10-ft-wide shoulder and 5-ft-wide sidewalk on each side. The basic information for the construction site is in Table 6, and the construction schedules for different assessed alternatives are described below.

- ABC method. ABC method requires I-4 to close one outside lane from 21:00 to 24:00 for only four nights. This schedule was obtained based on project documents.
- Conventional method I (Con I). Conventional method I requires I-4 to close two outside lanes from 21:00 to 24:00 for 48 nights. This schedule is a hypothetical schedule used in this study for further illustration of the methodology. The construction cost of Con I is assumed to be 15% higher than conventional method II, described below.
- Conventional method II (Con II). Conventional method II requires I-4 to close all the lanes from 21:00 to 24:00 for 32 nights. This is a schedule obtained from the project documentation.

Table 6. Basic Information for I-4/Graves.

Segment	No. of Lanes	Length (Miles)	Free Flow Speed (mph)
I-4-work zone	6 lanes	3.11	60
Detour for I-4	4 lanes	4.32	30
Graves Ave	2 lanes	0.83	45
Detour for Graves	2 lanes	1.91	30

4.1. Return-On Investment Analysis

It is well known that work zone capacity has a large influence on the estimation of mobility and reliability impacts and thus the road user costs. Since there is uncertainty in the open lane capacity during construction, sensitivity analysis was done in this study to determine the impact of this parameter value on the analysis results. Three values of the capacity were used and the impacts on performance results were compared. These values are: An estimate from a previous analysis

of real-world data by this study's researchers (capacity equal to 1000 veh/hr/lane), an estimate based on HCM 2010 procedure [33] (1136 veh/hr/lane), and an estimate obtained from a method derived in a recent research and implemented in the latest version of the HCM [43] (capacity equal to 1264 veh/hr/lane).

The return-on-investment (present worth) analysis results of the case study are shown in Table 7 and Figure 5 to Figure 6. As shown in Table 7, the construction cost of the ABC is higher than the conventional methods. If the comparison was done based on the construction cost alone, the agencies will select Conventional Method II. If the mobility (travel time delays due to construction) is added to the comparison, as is sometimes done when comparing construction and construction management alternatives, Figure 5 shows that Conventional Method I and the ABC alternatives have comparable costs and are lower than that of Conventional Method 2. When all components of the user costs were added to the analysis, Figure 6 indicates that the ABC is the best alternative. This illustrates the benefit of using the total costs in the comparison between ABC and conventional methods. If there are additional user costs, such as the impacts on businesses and toll revenue losses, if any were added, then the user cost could be even higher than that factoring the ABC alternative. In this project, I-4 was not a tolled highway and there was no impact on businesses that could be quantified.

Table 7. Sensitivity Analysis on Total Costs with Different Capacity.

Costs in Dollar Value (\$)		Mobility Impact	Reliability Impact	Safety Impact	Emission Impact	Construction	Construction Agency Costs	Total Cost
C = 1000 veh/hr/lane	ABC	120,347	32,807	40,864	1615	430,000	53,320	678,953
	Con I	224,591	258,414	77,313	2274	342,125	46,529	951,246
	Con II	487,838	258,580	127,434	3102	297,500	40,460	1,214,914
C = 1136 veh/hr/lane	ABC	120,347	32,489	40,864	1615	430,000	53,320	678,635
	Con I	191,339	202,851	77,207	2425	342,125	46,529	862,476
	Con II	487,838	258,580	127,434	3102	297,500	40,460	1,214,914
C = 1264 veh/hr/lane	ABC	120,347	32,311	40,864	1615	430,000	53,320	678,457
	Con I	183,026	73,715	77,207	2499	342,125	46,529	725,101
	Con II	487,838	258,580	127,434	3102	297,500	40,460	1,214,914

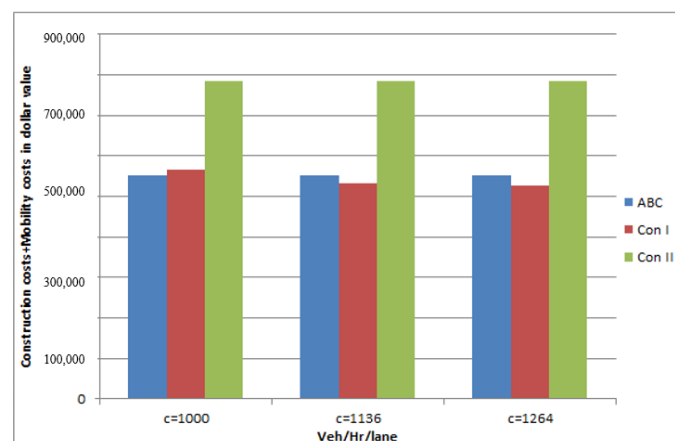


Figure 5. Comparison of the construction costs when only mobility cost is added to construction costs in the comparison.

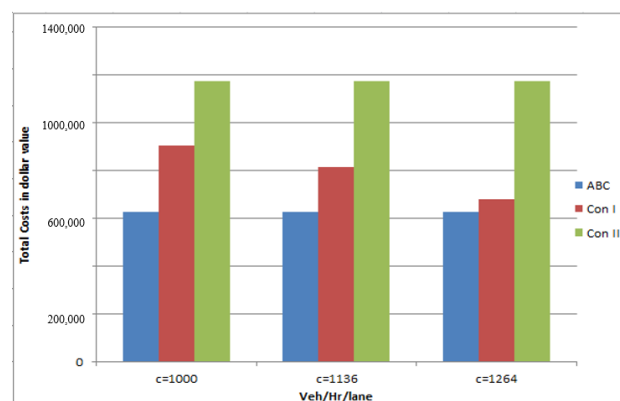


Figure 6. Comparison of the total costs of different alternatives with the consideration of the construction and user costs.

4.2. Fuzzy TOPSIS Analysis

The fuzzy TOPSIS approach was also conducted for the evaluation between ABC and conventional construction alternatives. The performance measure values do not have to be converted to a dollar value with this approach. The assessment of the various measures for different alternatives is shown in Table 8. The rating of these assessments based on the four expert's opinions is given in Table 9. The results from the TOPSIS analysis are shown in Table 10. In Table 10, D(max) represents the distance between the alternative to the best alternative, while D(min) represents the distance between the alternative to the worst alternative. CC shows the final utility of the alternatives. It can be found that the ABC alternative has a significant advantage compared to the other two alternatives when using the TOPSIS method that considers decision makers and preferences. Although the identification of the ABC as the best alternative is consistent with the conclusion from using the return-on-investment analysis described earlier, the magnitude of the advantage of ABC compared to the other methods is higher when using the TOPSIS MCDM method. As stated earlier, additional criteria can also be added to the MCDM analysis that cannot be added to the return-on investment analysis because their assessment results cannot be converted to dollar values, which is another significant advantage of the MCDM approach.

Table 8. Comparison of Different Alternatives.

Alternatives	Mobility Impacts (in veh-hr)	Reliability Impacts (in veh-hr)	Emission Impacts (in Ton)	Safety Impacts (Crashes)	Construction Costs (Direct Plus Agency)
ABC	7338	1444	2.79	0.79	483,320
Con I	11,667	9016	4.19	1.49	388,654
Con II	29,746	11,492	5.36	2.46	337,960

Table 9. Rating Results for Alternatives Based on Expert Criterion.

Alternatives	Mobility Impacts (in veh-hr)	Reliability Impacts (in veh-hr)	Emission Impacts (in ton)	Safety Impacts (crashes)	Construction Costs (Direct Plus Agency)
Expert1	ABC	VG	G	VG	MP
	Con I	G	MP	F	MF
	Con II	P	VP	P	VG
Expert2	ABC	VG	VG	VG	P
	Con I	G	F	F	P
	Con II	VP	VP	VP	VG
Expert3	ABC	VG	G	VG	VP
	Con I	F	MP	MF	MF
	Con II	VP	VP	VP	VG
Expert4	ABC	VG	G	VG	VP
	Con I	F	P	G	F
	Con II	VP	VP	VP	VG

Table 10. Fuzzy Evaluation Results.

Alternatives	D(max)	D(min)	CC
ABC	3.076	6.178	0.667
Con I	5.993	3.029	0.335
Con II	7.036	1.929	0.215

5. Conclusions

To deal with the pressing need to provide decision-makers with the appropriate tools to support the decisions associated with the selection between the ABC and conventional bridge construction, this paper presents an evaluation framework considering the total cost of the project that includes construction, agency, mobility, safety and ecological costs. Methods were developed to estimate these costs and to use these costs as inputs to the decision-making process to select between ABC and other alternatives. A new model was developed to allow the assessment of the construction cost of ABC relative to conventional construction. The main influencing factors on the construction cost were found to be the AADT, number of spans, location (urban versus rural), and ABC type. The examined data seems to indicate that the agency cost can be approximately calculated as 20% of the construction cost for both conventional and accelerated bridge construction. This study also demonstrated the estimation of user costs utilizing combinations of existing tools and methods. The estimated user cost components are related to mobility, reliability, safety, and emission impacts of the construction schedule.

This paper then compared the use of return-on-investment (present worth analysis) and MCDM evaluation approaches in the decision associated with the selection between ABC and conventional bridge construction. The return-on-investment analysis results indicate that the ABC can have a higher construction cost than conventional methods but its total cost can be lower, if all the elements of the user costs are added to the return-on-investment analysis.

The MCDM approach based on the TOPSIS method for the case study shows that the ABC alternative can be even more preferable, according to this method, than what can be concluded based on the return-on-investment analysis. This confirms the importance of accounting for agency priorities and user preference in the decision-making process of selection between ABC and conventional construction alternatives, as is done with the MCDM approach. Another advantage of using MCDM compared to return-on-investment analysis is that additional factors can be included in the decision process such as whether bridge location is on an evacuation route, schedule constraints, site constraints, impacts on business, impacts on freight, customer service, and so on.

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