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Estimating bridge performance based on a matrix-driven fuzzy linear regression model

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ABSTRACT

Determining a reliable bridge maintenance and rehabilitation strategy relies on accurate predictions of bridge conditions. Conventional regression cannot handle visual inspection results that are inherently non-crisp or linguistic. On the other hand, fuzzy regression provides an effective means for coping with such fuzzy data or linguistic variables. However, many of the existing fuzzy regression models require substantial computations due to complicated fuzzy arithmetic. This paper presents a multiple fuzzy linear regression using matrix algebra. The proposed model is capable of dealing with a mixture of fuzzy data and crisp data. Moreover, the approach is intuitive and easy to implement as compared to other related fuzzy regression models. A case study using bridge inspection data is presented to establish estimated fuzzy regression equations produced by the proposed approach and examine the factors contributing to overall bridge performance. The results demonstrate the capability of the approach, which can assist bridge managers to make better maintenance policies based on the future bridge conditions predicted by the model.

1. Introduction

Bridges are chief elements in the transportation system. Maintenance of highway bridges plays an important role to assure the desirable service and adequate reliability of highway networks. A primary goal of a Bridge Management System (BMS) is to assist bridge managers in determining the best bridge maintenance, repair and rehabilitation strategy with respect to current or future bridge conditions. In essence, the government funds available for maintaining existing bridges are usually limited. With restricted funds, maximizing the effect of the investment on the improvement of serviceability and safety of the existing highway system is the major challenge for highway agencies. For example, between 2003 and 2007, the percentage of the nation's 599,893 bridges rated functionally obsolete or structurally deficient decreased slightly from 27.1% to 25.59%. To eradicate all bridge deficiencies, it will cost 9.4 billion US dollars a year for 20 years; however, long-term budget is compounded by the shortage of the Highway Trust Fund [1].

Bridges are composed of several components including decks, girders, piers, cap beams, bearings, joints, abutments and foundation, etc. Typically, highway bridges are exposed to increasing traffic volumes and detrimental environmental conditions and have been built some decades ago. As a result, many highway bridges have been deteriorated or damaged. Bridge deteriorations may reduce functional performance such as loss of comfort for the road user, reduce structural reliability and require higher maintenance expenditure. A structurally deficient bridge may be closed or restricted to light vehicles because of its deteriorated structural components. Typical bridge defects include cracking, surface distortion, disintegration, rebar corrosion, expansion joint damage, waterproof deterioration, bearing damage, and foundation erosion, etc [2]. A major cause for bridge deficiencies is inadequate and ineffective maintenance activities.

In general, the bridge maintenance decision-making process comprises the steps of (1) assessing bridge condition, (2) forecasting bridge deterioration, (3) determining the most desirable maintenance strategy, (4) prioritizing maintenance actions, and (5) optimizing resource allocations [3,4]. Forecasting the future bridge conditions in advance is useful for taking required or urgent repair actions in order to avoid disastrous consequences. Accordingly, accurate predictions of future bridge conditions based on periodic bridge inspection results are essential to develop an optimal maintenance policy. To estimate a bridge's condition in future, approximately 60% of BMS depends on periodic bridge inspection results [5]. However, bridge inspection observations are innately imprecise or fuzzy because they are usually collected from the bridge inspector's visual and subjective assessments using linguistic descriptions such as “The condition of this pier is very good” or “The condition rating of this concrete deck is about 80”. On the other hand, data or variables affecting a bridge's condition including bridge age, traffic load, bridge geometry such as bridge span, and environmental condition (e.g., rainfall and temperature) are numerical or crisp. Consequently, information on current bridge condition is a mixture of crisp data and fuzzy data.

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Various techniques have been applied to predict bridge condition [6–9]. The Markov chain is one of the most widely used probabilistic state-of-the-art techniques for forecasting the performances of bridge infrastructures [10–12]. However, the main problem of this approach is the assumption that the future state of infrastructure components depends only on the present condition, which may affect its prediction accuracy. State-of-the-art infrastructure assessment also applies regression analysis [13]. Regression analysis is primarily used to find the best-fitted mathematical model, so that a dependent or response variable can be predicted from independent or predictor variable(s). Descriptions and controls of the cause-and-effect relationship between variables are also major purposes that regression analysis serves. However, conventional regression techniques are suitable for dealing with non-fuzzy data. To analyze data containing ambiguity and imprecision, fuzzy set theory is an effective approach [14].

Recently, numerous studies have been conducted using artificial intelligence techniques such as Artificial Neural Network (ANN) methods [15–17], Genetic Algorithms [18,19], and fuzzy techniques [20–23] to evaluate bridge conditions. Bridge conditions are usually difficult to precisely estimate because of uncertainties and vague information involving the process of inspection. Fuzzy regression analysis is suitable for coping with problems in which human experts rely on subjective judgment or rules-of-thumb. Tanaka et al. [24] proposed the first fuzzy linear regression analysis for crisp input and fuzz output data. Following their work, various developments of fuzzy regression techniques and applications have been accomplished [25–31]. Many of the existing fuzzy regression models require a great deal of computations because of difficult fuzzy arithmetic. The regression model proposed by Tanaka et al. is quite popular and useful; however, this model is restricted to symmetric triangular fuzzy numbers. To overcome this limitation, Chang and Lee developed a fuzzy least-squares regression model [28]. However, in their model, the regression coefficients are derived from a nonlinear programming problem that requires considerable computations.

This paper presents a matrix-driven multiple fuzzy linear regression model to overcome the difficulties arising from Chang and Lee's approach and other models that require complex fuzzy mathematics. The proposed approach can deal with asymmetric and symmetric triangular membership functions. Furthermore, by the use of matrix algebra, the model is simpler to follow and easier to apply. An illustration using this model for the estimation of overall bridge conditions is presented using actual bridge inspection data from Taiwan.

2. Estimation of bridge conditions

A degree-extent-relevancy-urgency evaluation method is implemented in the Taiwan Bridge Management System and is currently executed by the bridge administration units for rating bridge conditions. The performance assessment of each component of a concrete bridge is performed by bridge inspectors to assess the current degree of deterioration (D), extent of deteriorated area (E) relevancy to serviceability and safety (R), and the urgency of the action for repairing defects (U). Table 1 depicts the DER&U condition ratings [32–34]. As defined in the table, the deterioration conditions are described on a discrete and ordinal scale of 1, 2, 3, and 4 to represent the states of “Good”, “Fair”, “Bad”, and “Serious”, respectively. The condition indicator given by 1, 2, 3, or 4 is used to describe the extent of deteriorated area being less than or equal to 10%, 30%, 60%, and 100%, respectively. Correspondingly, the relevancy to safety and serviceability including “minor”, “restricted”, “major” and “considerable” is also represented by 1, 2, 3, and 4, respectively. Based on D, E, and R ratings, an appropriate bridge maintenance action can be determined amongst “routine maintenance”, “repair in 3 years”, “repair in 1 year”, and “repair immediately”.

Table 1
DER&U rating criteria.

Rating	Degree (D)	Extent (E)	Relevancy (R)	Urgency (U)
1	Good	<10%	Minor	Routine maintenance
2	Fair	10–30%	Restricted	Repair in 3 years
3	Bad	30–60%	Major	Repair in 1 year
4	Serious	60–100%	Considerable	Repair immediately

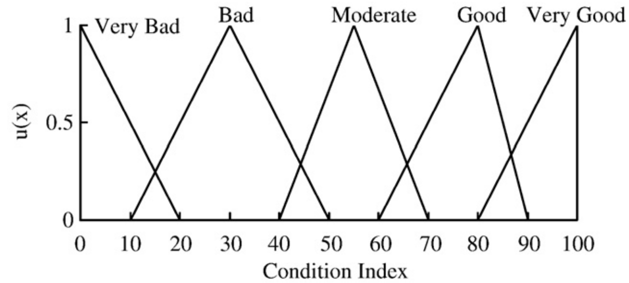

Fig. 1. Membership functions of bridge conditions.

Based on the inspection results, the condition of the component i can be estimated by using the performance index (PI). The calculation of PI is based on deterioration deduction points from the maximum score of 100 to the minimum score of 0, which is given by [32–34]

$$PI = 100 - 100 \times \frac{(D + E) \times R}{32}. \quad (1)$$

Concerning the assessment results for a given concrete deck: $D=2$, $E=2$, and $R=3$ as an example, the performance index of this concrete deck results in 62.5.

The overall bridge condition index (CI) can be defined as follows [32,33]:

$$CI = \frac{\sum_{i=1}^{n} PI_i \times w_i}{\sum_{i=1}^{n} w_i} \quad (2)$$

in which n is the number of the total components; w_i represents the relative importance or weight of each component from the inspector's point of view.

The relative weight in the above equation can be drawn from the use of Analytic Hierarchy Process (AHP). Since human inspector's assessment is naturally imprecise, the use of Eqs. (1)–(2) may not adequately represent overall bridge conditions. Furthermore, the DER&U ratings only define four levels of deterioration conditions, which overlook a necessary condition like very good or excellent. This type of condition is usually associated with newly constructed or repaired bridges. Hence, this paper defines five linguistic terms, Very Bad (VB), Bad (B), Moderate (M), Good (G), and Very Good (VG), corresponding to a nominal scale ranging from 0–100% to represent deterioration degrees. A questionnaire is used to direct seven experts to appraise these five linguistic terms. These experts are bridge inspectors who have more than ten-year working experience in bridge assessment. Typical questions are as follows:

> “On a scale rating from 0% to 100% condition index values with increments of 5%, please indicate (1) a likely range, and (2) a most-likely value that can best represent bridge conditions being *Very Good*?”

Similarly, the rest four linguistic terms can be measured through the survey. Based on the final agreement, the membership functions used to characterize the five levels of bridge conditions are constructed as shown in Fig. 1. It can be found in Fig. 1 that “Very Bad” and “Very Good” are represented by half triangular membership functions. “Good” is described by an asymmetric triangular