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Bridge Service Life Estimation Considering Inspection Reliability

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Abstract

Bridges begin to deteriorate as soon as they are put into service. Effective bridge management requires sound understanding of the deterioration mechanism as well as the expected service life. Decision makers design and execute programs that safely maintain or extend bridge service life at low cost. Key maintenance practices include inspections, repairs, and rehabilitation, among which inspections may be the most important since the other maintenance interventions are conducted based on the inspection report. This paper presents a methodology for determining the expected service life of a bridge or a bridge network based on a deterministic condition-based model associated with inspection quality. This study used almost 10-year condition rating results of bridges and developed a non-linear regression model that takes into account the Inspection Reliability Index (*IRI*). The *IRI* represents the relative inspection accuracy with respect to a tolerable error of one grade by comparing condition ratings between routine and in-depth safety inspections. In the evaluation of the *IRI*, significant variability in condition ratings between routine and in-depth safety inspections was observed. Specifically, approximately 42% of routine inspection results deviated within ± 1.0 grade with respect to results from in-depth safety inspections. A modified non-linear regression model combined with the *IRI* is proposed to predict the remaining service life of a bridge. The proposed model can estimate the service life of a bridge by combining the bridge age and its condition rating.

Keywords: *bridge management, condition-based model, service life, inspection practice, inspection reliability*

1. Introduction

A bridge starts to deteriorate as soon as it is put into service. A solid understanding of expected bridge life is an essential part of effective bridge management. Expected bridge life is generally defined as the time until the bridge is retired, replaced, or removed from service. Determining when a bridge reaches the end of life is a comprehensive decision-making process that entails consideration of the cost and effectiveness of follow-up actions (repair/rehabilitation) corresponding to accurate condition ratings. Effective management of a bridge requires decision makers to design and execute programs that maintain or extend bridge life at low cost.

Agencies use estimates of bridge service life in management programs, but the estimates depend on maintenance practices, material quality, service conditions, and other factors. Better information and tools for estimating bridge life are required to guide in-service bridge management programs. The core components of estimating bridge life are appropriate deterioration models and accurate bridge condition ratings. For this reason, a Bridge Management System (BMS) has been developed to provide the decision-makers with timely maintenance strategies for a bridge or a bridge network based on estimates of bridge life in conjunction with accurate bridge condition rating.

The BMS called PONTIS was developed in the U.S. in 1991 and is used widely by the U.S. Department of Transportation (DOT) (FHWA, 2012). BRIDGIT is a BMS that primarily targets local highway systems and is also used in the U.S. DOTs (FHWA, 2012; Hawk, 1999). This BMS analyzes bridge service life using bridge deterioration models based on condition ratings to determine the timely maintenance interventions necessary to rectify any deterioration.

In the past two decades, a number of bridge deterioration models that can be integrated into a BMS have been developed to predict service life expectancies of bridges. These models can be broadly categorized as deterministic approaches and probabilistic approaches (Agrawal *et al.* 2010; Estes and Frangopol, 2001; Klatter and Van Noortwijk, 2003; Morcous, 2006; Sanders and Zhang, 1994). When choosing among the modeling approaches, it is extremely important for agencies to consider the availability

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of data because the accuracy of bridge life predictions hinges on the availability and quality of databases.

Among the deterministic models, regression models are the most commonly applied technique due to their easy application and interpretation, simplicity of methodology, and clarity of results. Regression models can be applied to predict a continuous performance measure (condition-based) as a function of age (Sanders and Zhang, 1994; Thompson *et al.,* 2012a). The probabilistic models treat the bridge deterioration process as a random variable that captures the uncertainty and randomness of the process. Of the probabilistic models, Markov chains applications can predict the probability of a bridge being in any state at any point in time (Agrawal *et al.,* 2010; Morcous, 2006). A survival model is a probabilistic approach for predicting the likelihood of a continuous dependent variable (e.g., bridge condition) passing beyond or "surviving" at any given unit of time (Klatter and Van Noortwijk, 2003).

Despite these research achievements in the development of deterioration models, the fundamental problem of the limited amount of bridge inspection data remains. In particular, the Markovian model and the survival model require a number of inspection data of "failed" bridges. "Failed" does not necessarily mean literally "falling down" or "shutting down traffic" but rather that a bridge or a bridge element in the worst condition state is a strong candidate for replacement (Thompson *et al*., 2012b). If extensive data on intervals between replacements are available, the survival model can be applied for life expectancy estimation. If condition data are discrete in nature and routinely collected during inspections, Markov-based modeling can be applied. However, it is necessary to define "failed" as the worst of the defined condition states, and a number of data that conform to the definition of a failed condition should be available (Thompson *et al*., 2012b). If condition data routinely collected during inspections as a function of age are available, the regression model can be applied directly to bridge life even without data on the failed condition (Agrawal *et al*., 2010).

Bridges last much longer than do bridge elements. For a transportation agency, bridges are a long-term investment. During its life cycle, a bridge requires both routine and periodic maintenance, rehabilitation and replacement work in need. Thus, bridges require a series of expenditures for various activities during their life cycles. From the point of view of the decision-makers who determine design, construction, and maintenance budgets, the less-detailed perspective is generally adequate. It does not matter that particular elements of the bridge are more deteriorated than others, when overall loading capacity remains adequate and maintenance crews can deal with whatever problems they face. Thus, it is useful to focus more on developing BLCCA (Bridge Life Cycle Cost Analysis) algorithms for the bridge than individual element of the bridge. For example, the NBI sufficiency rating in U.S. are more widely used to determine current or future network-level needs for maintenance of bridges than NBI condition ratings for individual bridge elements. In practice, some states in U.S. use the sufficiency rating as the basis for priorities for repair or replacement of bridges (FHWA, 2012). When the sufficiency rating first reaches or drops below 50%, this corresponds to the level at which a bridge may qualify for HBRRP (Highway Bridge Replacement and Rehabilitation Program) federal funding (Thompson *et al.,* 2012b). In this paper, from the point of view of the decision-makers, the condition-based/age-based model for network-level were considered to be the prediction of bridge service life, rather than individual bridge components.

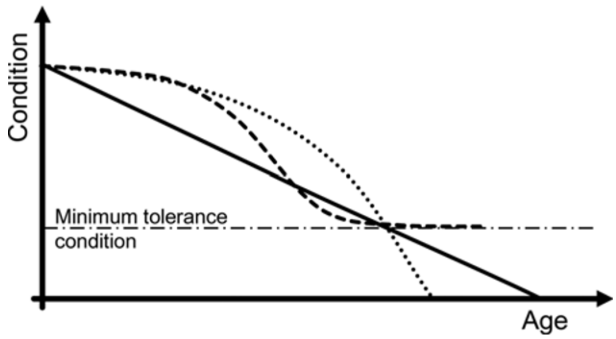

Fig. 1. Various Patterns of Bridge Deterioration

There are several mathematical methods of deterministic approaches for predicting the service life of a bridge. These methods include straight-line extrapolation, non-linear regression, and sigmoidal (see Fig. 1). In this study, the non-linear regression model was selected for estimating bridge service life because of the limited number of failed bridges in South Korea. If the known bridge life span does not vary much from one agency to another, the shape of the mathematical curve can be determined by regressing. Subsequent enhancements make the curve sigmoidal or s-shaped, so it would approach the minimum tolerance condition asymptotically (Thompson *et al*., 2012a).

The bridge inspection process is critical to ensuring bridge safety, identifying needs of repair/rehabilitation, and determining the appropriate allocation of budget. The quality of inspection data is important for providing decision-makers with appropriate strategies for a bridge or a group of bridges. For example, agencies can implement long-term strategies for funding bridge replacements or reducing the number of deficient bridges based on long-term life expectancy models, which require accurate condition ratings. The procedure to improve the quality level of inspections, typically described as Quality Control (QC)) has been recognized. However, according to a literature review on inspection quality, it was found that bridge condition documentation is collected with significant variability (Graybeal *et al.,* 2002; Phares *et al.,* 2004).

Graybeal *et al*. (2002) evaluated the reliability of visual inspections of highway bridges, and their findings indicated that the condition ratings normally assigned through the routine inspection process can vary significantly. Specifically, approximately 68% of inspection results vary within ± 1.0 NBI (National Bridge Inventory) rating from the average based on a statistical analysis (FHWA, 2012; Phares *et al*., 2004). Such inaccuracy and inconsistency of the condition ratings may result in inappropriate maintenance strategies, which can jeopardize bridges and users. It is therefore necessary to develop a measure for evaluating inspection reliability of bridges to improve inspection quality.

Agencies have faced challenges in ensuring acceptable performance of bridges with respect to condition, safety, reliability, and life cycle cost, and several research groups have tried to estimate bridge service life and inspection reliability (Agrawal *et al.,* 2010; Estes and Frangopol, 2001; Graybeal *et al*., 2002; Klatter and Van Noortwijk, 2003; Phares *et al*., 2004). Hybrid deterioration models combine a probabilistic approach and a corrosion-induced deterioration model to characterize the deterioration behavior of bridges more realistically (Lounis and Madanat, 2002; Morcous and Lounis, 2007; Roelfstra *et al*., 2004). However, combining a bridge service life expectancy model with the reliability of the inspection process has not been researched previously.

This paper presents a methodology for determining the life expectancies of a bridge or bridge network based on an average deterioration model accounting for inspection reliability. The life expectancy model developed in this study consists of two parts: (i) a non-linear regression model and (ii) a non-linear regression model adjusted by the Inspection Reliability Index (*IRI*). The non-linear regression model performs lifetime profile computations of bridges using condition ratings inspected for 10 years. The second model adjusted by *IRI* represents the inspection accuracy with respect to a tolerable error of ± one grade, which is evaluated by comparing 9-year bridge condition ratings from routine inspections to in-depth safety inspections. The modified regression model considering the *IRI* is proposed to estimate expected bridge service life and remaining service life.

2. Bridge Inspection

2.1 Bridge Inspection Practice in South Korea

In South Korea, the inspection manual defines a routine inspection that is conducted every 6 months. Other inspections such as in-depth, emergency, and in-depth safety inspections can be scheduled independently from a routine inspection, although generally at longer intervals or as a follow-up for other inspection types. Fig. 2 presents a flow chart of bridge inspections performed in South Korea. Generally, the routine inspection is the scheduled visual inspection which is completed biannually to

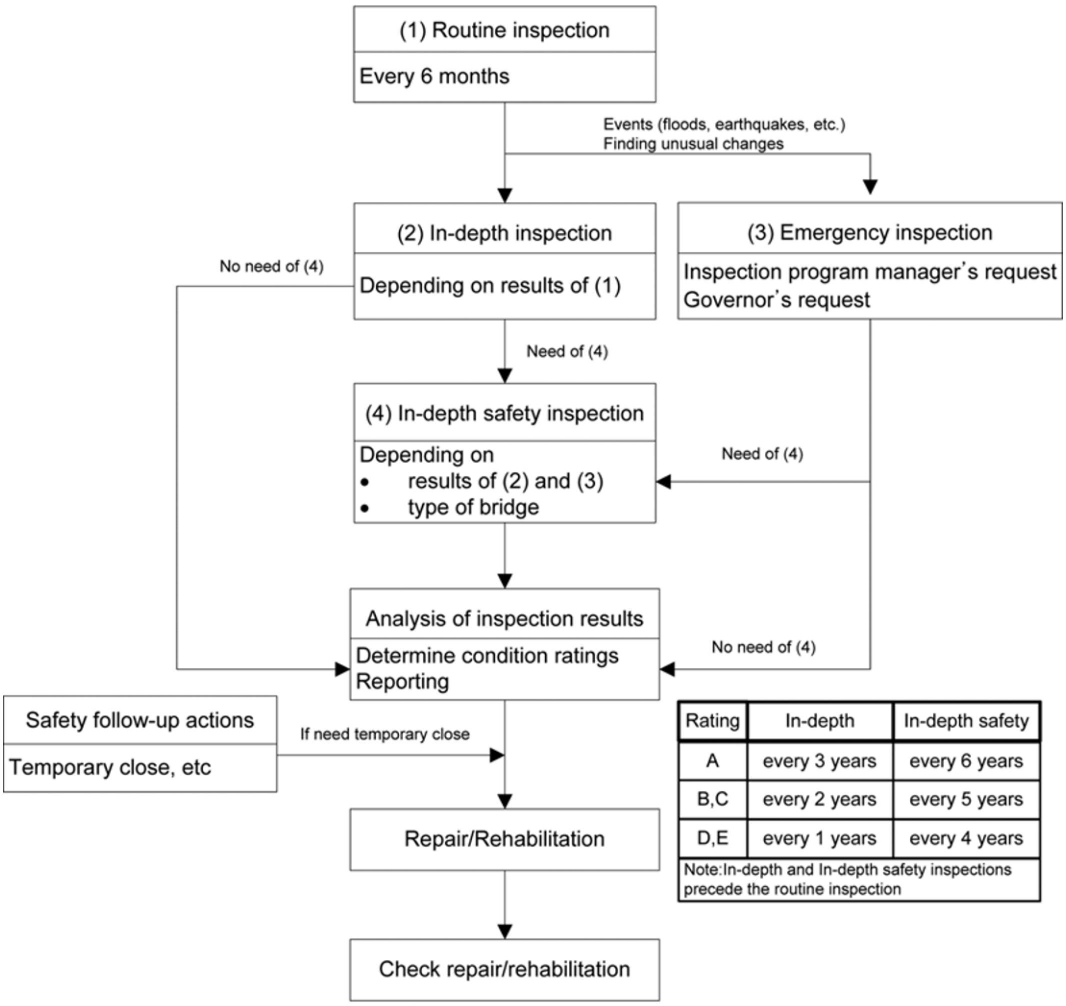

Fig. 2. Flow Chart of Bridge Inspections in South Korea (MOLIT, 2012a)

determine the physical and functional condition of a bridge. On the other hand, the in-depth safety inspection is the close-up and hands-on inspection which is completed on standard-designated bridges to identify deficiencies not readily detected during routine inspections (MOLIT, 2012a). In general, the in-depth safety inspection is completed at longer intervals than the routine inspections and includes the use of more advanced non-destructive evaluation (NDE) techniques.

To evaluate the bridge condition, transportation agencies use a damage score (*DS*), which is the normalized sum of the weighted damage index (*DI*) of an element, as shown in Table 1. The *DI* is a representative value of each condition rating. The *DS* of an entire bridge is evaluated as follows:

$$Damage\ Score,\ DS_B = \frac{1}{100}\sum_{i=1}^{n} DI_e^i \times WF_e^i$$

$$\sum_{i=1}^{n} WF_e^i = 100 \quad (1)$$

where DS_B is the damage score of an individual bridge, DI_e^i is the damage index of the i^{th} element, and WF_e^i is the weighting factor of the i^{th} element. In practice, the damage score of a new bridge, when it opens to traffic, should be 0.1 in an accordance with Eq. (1), because the damage index of an element in perfect condition is 0.1. In other words, although a new bridge is in perfect condition, its damage score should not be less than 0.1 value. Table 1 presents descriptions for each condition rating including *HI* (Health Index, *HI* = 1-*DS*). It is noteworthy that *HI* was used to estimate life expectancy of a bridge instead of *DS*. Typical life curve (or performance condition curve) for estimating life expectancy of bridges is the declining pattern over time. *HI* may range from 0, corresponding to the worst possible health, to 0.9 for the best possible health in perfect condition. For this reason, *HI* was used for the life curve in lieu of *DS* in this study.

2.2 Bridge Inspection Practice in U.S.

In U.S., the types of bridge inspections are various to reflect the intensity of inspection required at the time of inspection. The AASHTO manual defines seven types of bridge inspections, allowing a bridge owner or state DOTs to establish their own appropriate inspection levels that are consistent with the inspection frequency and types of structures defined by AASHTO and the National Bridge Inspection Standards (NBIS) (AASHTO, 2013; FHWA, 2004; FHWA, 2012). Table 2 lists inspection types and brief descriptions defined in the AASHTO manual (AASHTO, 2013). Routine inspections are visual condition inspections that evaluate the physical and functional conditions of bridges and are equivalent to Korean routine inspections but conducted biennially. These inspections should identify any changes in condition from the previous inspection and ensure that the bridge continues to meet all applicable serviceability requirements. On the other hand, in-depth inspections are close-up and hands-on inspections, generally of a limited portion of a bridge, completed

Table 1. Conditions Ratings in Korea (MOLIT, 2012b)

Rating	*DI*(1)	*DS*(2)	*HI*(3)	Descriptions
A	0.1	$0.0 \le DS < 0.13$	$0.87 < HI \le 1.0$	Perfect, no problems
B	0.2	$0.13 \le DS < 0.26$	$0.74 < HI \le 0.87$	Good condition: Needs small repairs for improvement in durability
C	0.4	$0.26 \le DS < 0.49$	$0.51 < HI \le 0.74$	Poor condition: needs repairs in primary elements or rehabilitation in secondary elements
D	0.7	$0.49 \le DS < 0.79$	$0.21 < HI \le 0.51$	Critical condition, needs of emergency repairs or rehabilitation
E	1.0	$0.79 \le DS$	$HI \le 0.21$	Failure condition: needs of rehabilitation or replacement

1 *DI*: Damage Index
2 *DS*: Damage Score
3 *HI*: Health Index

Table 2. U.S. Inspection Types and Intervals (AASHTO, 2013; FHWA, 2004)

Inspection	Description	Interval
Initial	• First inspection of a bridge as it becomes a part of the bridge inventory to provide all subsequent inspections relevant data to determine baseline structural conditions.	at bridge open
Routine (Periodic)	• Regularly scheduled inspection consisting of observations and/or measurements needed to determine the physical and functional condition of the bridge.	≤ 24 months
Damage	• An unscheduled inspection to assess structural damage resulting from environmental factors or human actions.	Various*
In-depth	• A close-up inspection of bridge to identify any deficiencies not readily detectable using routine inspection procedures.	Various
Fracture-critical	• A hands-on inspection of a fracture-critical member or member components that may include visual and other nondestructive evaluation.	≤ 24 months
Underwater	• Inspection of the underwater portion of a bridge substructure and the surrounding channel.	≤ 60 months
Special	• An inspection scheduled at the discretion of the bridge owner, used to monitor a particular known or suspected deficiency.	Various

*Various: A bridge owner or state DOTs can determine intervals for damage, in-depth, and special inspections.

Table 3. Comparisons of Condition Ratings of South Korea and U.S. (FHWA, 2012; MOLIT, 2012b)

Descriptions of NBI rating	U.S.[1] NBI rating	South Korea[2] HI or HI_e (DS)	South Korea[2] Rating
EXCELLENT CONDITION	9	$0.87 < HI \le 1.0$ ($0.0 \le DS < 0.13$)	A
VERY GOOD CONDITION: no problem noted.	8		
GOOD CONDITION: some minor problems.	7	$0.74 < HI \le 0.87$ ($0.13 \le DS < 0.26$)	B
SATISFACTORY CONDITION: structural elements show some minor deterioration.	6		
FAIR CONDITION: all primary structural elements are sound but may have minor section loss, cracking, spalling, or scour.	5	$0.51 < HI \le 0.74$ ($0.26 \le DS < 0.49$)	C
POOR CONDITION: advanced section loss, deterioration, spalling, or scour.	4		
SERIOUS CONDITION: loss of section, deterioration, spalling, or scour have seriously affected primary structural components. Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present.	3	$0.21 < HI \le 0.51$ ($0.49 \le DS < 0.79$)	D
CRITICAL CONDITION: advanced deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present or scour may have removed substructure support. Unless closely monitored it may be necessary to close the bridge until corrective action is taken.	2		
"IMMINENT" FAILURE CONDITION: major deterioration or section loss present in critical structural components, or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic but corrective action may put bridge back in light service.	1	$0.0 < HI \le 0.21$ ($0.79 \le DS < 1.0$)	E
FAILED CONDITION: out of service; beyond corrective action.	0		

[1]Bridge Inspector's Reference Manual, FHWA-NHI-12-049, 2012
[2]Korean Guideline and Commentary for Safety Inspection and In-depth Safety Inspection for Structures-Bridge, 2012

to identify deficiencies hardly detectable during routine inspections. In-depth inspections are focused on locating specific defects that may exist in the bridge.

In U.S., state DOTs report NBI data as required by the NBIS and describe the nation's bridges. The NBI conditions reflect the range of the physical conditions of major bridge components such as the deck, superstructure, substructure, culvert, and sub-elements. The NBI defines condition states ranging from 0 to 9 (see Table 3) (FHWA, 2012). The NBI condition rating does not represent the overall condition of the overall bridge. The descriptions in Table 3 are general guidelines for evaluation of the deck, superstructure, and substructure (FHWA, 2012). The condition rating, however, shows the localized condition of the primary elements of the bridge. In other words, the NBI condition rating indicates how well the major elements of a bridge function rather than how well the entire bridge functions.

For the purpose of comparison, the *HI* condition ratings in South Korea are also included in Table 3. For the sake of clarity, the bridge element condition ratings (HI_e) are available in terms of $HI_e = 1 - DI_e$, and the bridge condition rating (*HI*) can be found from $HI = 1 - DS$, which is computed by multiplying the element HI_e ratings by weighting factors (*WF*s) (MOLIT, 2012b). The ratings in the same row do not necessarily represent the same rating but exhibit comparable ratings between the two countries. Compared to the South Korean ratings, the NBI ratings of the U.S. are categorized in greater detail into nine groups corresponding to each condition, so the NBI rating system was determined as a reference to condition ratings of South Korea.

3. Data Processing

The condition and performance of a bridge can be input variables for a life expectancy model or long-term decision-making process to plan preventive maintenance actions, repairs, rehabilitation, and replacement (Thompson *et al.*, 2012a). The life expectancy model was developed using *HI* (Health Index) of an individual bridge. Highway bridges in South Korea have been managed using the Korea Highway Bridge Management System (KHBMS) since 2000 (Cho *et al.*, 1999), and bridge inspection data are available for 2004 and later. Hence, bridge inspection data for 2004 to 2013 were used to develop the *HI* curve for highway bridges. Inspection data of all bridges include all maintenance such as preventative maintenance, repairs, and rehabilitation.

4. Estimation of Expected Bridge Service Life

4.1 End-of-life Criterion

Life expectancy models such as deterministic or probabilistic models are developed using a set of existing bridge data to predict future behavior (Agrawal *et al.,* 2010; Estes and Frangopol, 2001; Klatter and Van Noortwijk, 2003; Morcous, 2006; Sanders and Zhang, 1994). They all require past condition data and past maintenance and replacement activities. If sufficient past replacement data are not available, then it is necessary to have a criterion that reliably shows a condition threshold when replacement would be required. In other words, it is necessary to have a clear criterion of the end-of-life (EOL). It is critical to select a representative condition pertinent to the bridge replacement rationale under consideration. When the EOL refers to service life, an appropriate measure of bridge condition and an agency-specified condition threshold are needed. For example, any bridge classified as structurally deficient for which deck, superstructure or substructure are rated in NBI condition equal to 4 or less (FHWA, 2012;

Thompson *et al.*, 2012a).

A minimum acceptable threshold or trigger is needed for estimation of the bridge life expectancy given a quantitative measure such as bridge condition ratings. In South Korea, when a bridge condition is equal to D or below ($DS \geq 0.49$, see Table 1), the agency considers a traffic closure (MOLIT, 2012b). When a bridge condition is equal to E ($DS \geq 0.79$), emergency load restrictions or immediate traffic closure should be implemented, and it is necessary to assess the level of damage to rehabilitate or replace the bridge. Hence, a traffic closure can occur for bridge maintenance when the bridge condition rating is equal to D or below. As a result, the EOL condition threshold for highway bridges in this study is chosen as $DS_{EOL} = 0.64$ (the mid-point of rating D), which is equivalent to $HI_{EOL} = 0.36$.

For comparison, the EOL of primary bridge elements in U.S. (e.g., the deck, superstructure, or substructure) can be defined as when the NBI condition ratings are equal to 2 or below (see Table 3). When any of the NBI condition ratings of three primary bridge elements is 4 or below, the bridge becomes eligible for federal funding for replacement (Thompson *et al.*, 2012b). Because of funding scarcity, pre-construction activities, or related road network plans, agencies may allow a bridge to remain at condition level 4 or even 3 for many years before replacing the structure. In practice, a bridge closure can occur when the NBI condition ratings are equal to 2 or below. For the sake of clarity, the EOL of a bridge does not mean that the bridge has structurally failed or collapsed (Thompson *et al*., 2012b). It may mean that replacement is highly recommended for a bridge in the worst condition. Typically, this threshold is chosen to reflect the point at which intermediate maintenance actions are no longer cost-effective (Saito and Sinha, 1989).

4.2 Non-linear Regression Model for Estimating Bridge Expectancy Life

A regression model with a condition-based approach was used for predicting bridge life expectancy. In general, the condition-based approach has been used for estimating the functional life or service life of high-value assets (i.e., bridges) (Thompson *et al*., 2012b). The conditions of these assets are monitored and inspected regularly. Regression models are the most commonly applied technique by agencies for bridge condition modeling due to their easy application and interpretation.

Non-linear regression models are used to establish an empirical relationship between a dependent variable and one or more independent variables. Curve fitting was used to develop a condition-based model for a bridge network. The form of the non-linear regression model is as follows (Patterson, 1987):

$$HI = I - (I - HI_{EOL})\left(\frac{T_a}{T_{as}}\right)^{\beta} \quad (2)$$

where HI is the bridge health index (HI = 1-Dmage Score), I is the initial value of the HI curve representing the condition when a bridge is put into service which is 0.9, β is the slope of the HI curve, T_{as} is the average service life, HI_{EOL} is the HI value for the EOL condition threshold (= 0.36), and T_a is the age of a given bridge.

Bridge condition rating data covering 10 years was used for curve-fitting and are listed in Table 4. The HI curve was estimated by minimizing the sum of squares of the differences between the observations and predicted values (T_{as} and β) as shown in Eq. (3).

$$HI = 0.9 - 0.54\left(\frac{T_a}{T_{as}}\right)^{\beta} \quad (3)$$

where, $T_{as} = 70.8$ and $\beta = 1.706$

The HI curve for all bridges in Fig. 3 clearly shows the time dependence of the declining pattern. The average service life of highway bridges in South Korea was 70.8 years. The average service life is the predicted time it will take for the bridges to reach a minimum acceptable condition value ($HI_{EOL} = 0.36$). Due to limited amount of bridge inspection data such as lack of bridge reconstruction records, the interpretation of results can be limited. These censored data are partially observed bridge lives, where the year built but no year reconstructed is known. These estimates include bridges that have not yet reached the end-of-life threshold in these estimates. To explain life expectancies when including censored observations, various factors in the inspection database should be analyzed in the modeling process for further study. These factors include the following: geometrics (e.g., structure length and deck width), geographic data (e.g., county, state, rural, and urban), material type (e.g., concrete and steel), structural type (e.g., beam and slab), inspection quality (e.g. inspection accuracy), and traffic loadings (e.g., ADT

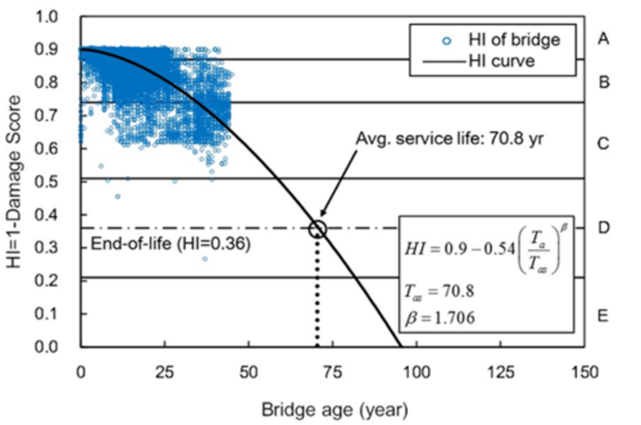

Fig. 3. *HI* Curve for Inspected Highway Bridges

Table 4. Bridge Data used to Develop Deterioration Model

	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	Total
Total	4,395	5,669	5,768	5,815	6,459	6,943	7,186	7,627	8,002	6,389	64,253

(Average Daily Traffic) or ADTT (Average Daily Truck Traffic)). Of these factors in this paper, inspection quality by means of inspection reliability index was considered to explain life expectancy after including censored data. In further study, life expectancies of bridges will be estimated with taking into considerations structural types, material types and etc.

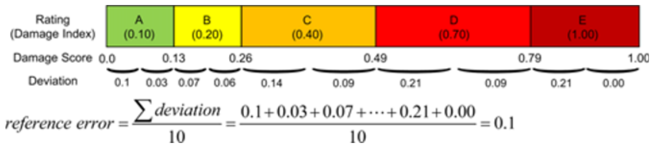

Fig. 4. Derivation of Reference Error

5. Inspection Reliability

Given that inspection quality leads to successful bridge maintenance and management, the quality level of inspections should be improved through effective QC procedures. This section provides a measure to evaluate inspection reliability as a QC procedure by comparing bridge condition ratings between the routine inspections and the in-depth safety inspections. Two types of bridge inspections were considered: routine and in-depth safety inspections. The condition ratings of the in-depth safety inspections are assumed to be the "true" values for evaluation of the inspection reliability since the in-depth safety inspections are hands-on, detailed, and thorough inspections that are expected to locate defects precisely.

Percent error (or deviation) is a measure of the accuracy of any measured value with respect to the reference value. Using percent error, the inspection reliability index (*IRI*) is proposed as follows:

$$\text{Percent Error} = \left(1 - \frac{e_I}{e_0}\right) \times 100 \tag{5}$$

$$IRI(\%) = \left(1 - \frac{e_I}{e_0}\right) \times 100 = \left(1 - \frac{\sum_{i=1}^{N} |e_I^i|}{e_0 \times N}\right) \times 100 = \left(1 - \frac{\sum_{i=1}^{N} \left|HI_{Routine}^i - HI_{In\text{-}depth\ safety}^i\right|}{0.1 \times N}\right) \times 100 \tag{6}$$

where e_I^i = is the inspection error of the i^{th} bridge, $e_I^i = HI_{Routine}^i - HI_{In-depth\ safety}^i$,

e_0 = is the reference error representing deviation of ± one grade ($e_0 = 0.1$),

N = is the total number of bridges used to evaluate *IRI*,

$HI_{Routine}^i$ = is the *HI* value of i^{th} bridge evaluated from the routine inspection,

$HI_{In-depth\ safety}^i$ = is the *HI* value of i^{th} bridge evaluated from the in-depth safety inspection.

The reference error of 0.1 was derived from the average deviation of the damage score from the damage index, which is the representative value of each rating (Fig. 4). This indicates that when the absolute value of inspection error $|e_I|$ is greater than the reference error ($e_0 = 0.1$), the bridge condition rating would change on average (Fig. 4). Generally, a tolerance within ± 1 condition ratings may be accepted due to the limitation of the routine inspection procedure in the proposed formula. Thus, *IRI* represents a relative routine inspection accuracy with respect to ± 1 condition ratings.

It can be seen from Eq. (7) that the relationship between the inspection error e_I and *IRI* can be determined. The smaller the inspection error is, the greater the higher accuracy (the maximum *IRI* is 100%). The larger the inspection error is, the lower the accuracy is achieved. For example, when the inspection error is 0.1, the *IRI* is *zero* percent, which means a ± 1 rating difference. Figure 5 shows an example of the relationship between *IRI* and inspection error.

$$Inspetion\ error,\ e_I = 0.1 - 0.1 \times \frac{IRI}{100} \tag{7}$$

The *IRI* was evaluated by comparing bridge condition ratings between routine inspections performed in the previous year and in-depth safety inspections performed in the current year (e.g., routine inspection *HI* rating in 2012 versus in-depth safety inspection *HI* rating in 2013). This is based on the assumption that a bridge condition does significantly change within a year (Fig. 3). Table 5 shows the number of bridges inspected using in-depth safety inspection procedures.

Table 6 summarizes the statistical information on the *IRI* evaluated using the inspection error between routine and in-depth safety inspections. The maximum inspection error is 0.28, which can lead to a change of two grades in the condition ratings on average (see Table 6). The mean value (μ) and the standard deviation (σ) of the inspection error were both 0.05. Assuming a normal distribution for the inspection error, 68.2% ($\mu + \sigma$) of routine inspection results varied within ± 1 grade from the results of in-depth safety inspections based on a statistical analysis, as shown in Fig. 6(b).

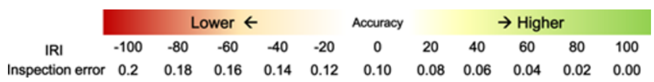

Fig. 5. Relationship between *IRI* and Inspection Error

Table 5. In-depth Safety Inspection Data used to Evaluate Inspection Reliability

Year	2005	2006	2007	2008	2009	2010	2011	2012	2013	Total
No. of bridges	20	33	117	143	94	125	149	259	175	1,115

Table 6. Inspection Reliability Index Statistics

	In-depth safety inspection (I_1)	Routine inspection (I_2)	Inspection error (I_1-I_2)
Mean (μ)	0.80	0.85	0.05
Standard deviation (σ)	0.05	0.05	0.05
Distribution	$0.50 \le HI_1 \le 0.90$	$0.57 \le HI_2 \le 0.90$	$-0.20 \le HI_1\text{-}HI_2 \le 0.28$
IRI	42%		

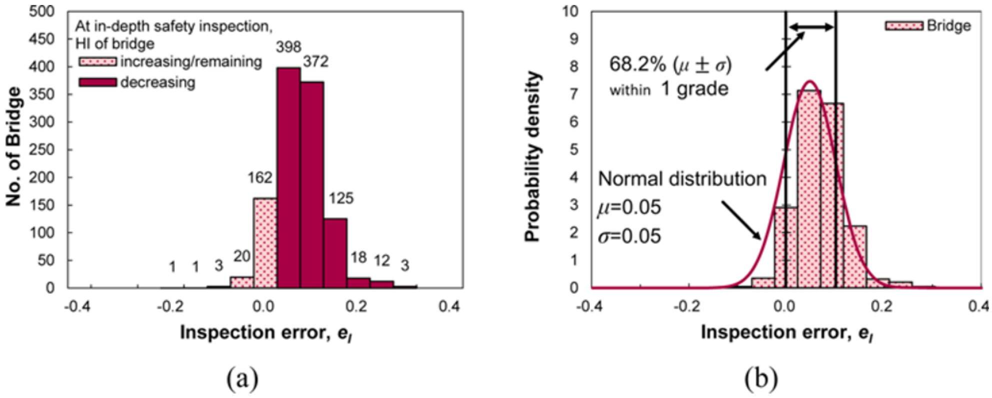

Fig. 6. Distribution of Inspection Error (e_I) between Routine and In-depth Safety Inspections: (a) Number of Bridges, (b) Probability Density

An evaluation of the reliability of visual inspection published by the FHWA in 2001 indicated that the condition ratings normally assigned through the routine inspection process varied significantly (Moore *et al.,* 2001). Specifically, 95% of primary element condition ratings (e.g., the deck, superstructure, and substructure) varied within ± 2 NBI rating points of the average, and 68% varied within ± 1 NBI condition rating. The standard deviation of *HI* rating was 0.05 for both routine and in-depth safety inspections, illustrating the level of dispersion of inspection results about the mean. The *IRI* evaluated using inspection results of 1,115 bridges was 42%, which means that the average inspection error of routine inspections was 0.058 using Eq. (7) compared to in-depth safety inspections. A histogram for the inspection error is shown in Fig. 6(a). The *HI* values of 928 inspected bridges (83% of the total 1,115 bridges) obtained using in-depth safety inspections were smaller than the routine inspection results (see Fig. 6(a)), indicating that the real bridge conditions are worse than the bridge conditions reported by routine inspections.

Typically, life expectancy and deterioration models have been adjusted separately for material type (e.g., concrete or steel). Among the models adjusted for concrete structures, the life expectancy factors include the following: climatic conditions, geometry (e.g., deck area), age, traffic volume, and accumulated truck loads (Adams *et al*., 2002; Chang and Garvin, 2006; Rodriguez *et al*., 2005; Testa and Yanev, 2002). The regression model was adjusted to the *IRI*. It was assumed that *HI* values obtained from the in-depth safety inspection procedure are the correct condition rating reflecting the real condition of bridges, since the 928 *HI* values evaluated from the in-depth safety inspection are smaller than those evaluated from the routine

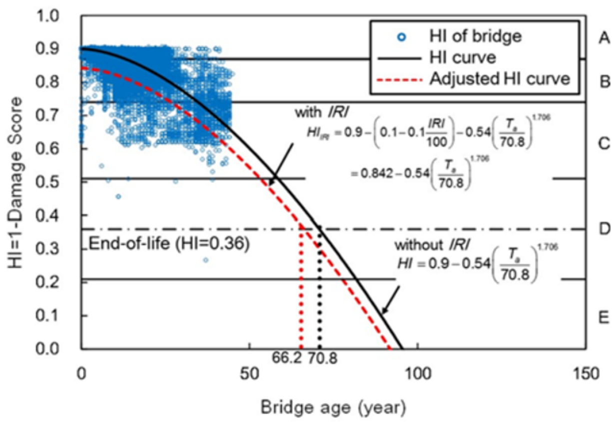

Fig. 7. Adjusted *HI* Curve Based on *IRI*

inspection. The real bridge conditions are worse than what is reported from routine inspections, so the *HI* curve is vertically shifted down by the inspection error of 0.058, which is calculated by Eq. (7) with *IRI* of 42% (Fig. 7). The regression model calibrated to the *IRI* would suggest an average service life of 66.2 years, as shown in Fig. 7.

Inconsistencies and inaccuracies in the *HI* ratings between inspection types can be explained by several sources, including variations between different inspectors, inadequacies in training, or procedures and practices. Variance in the inspection results between different inspectors can have several sources, including (i) variations in training, education, and experience; (ii) understanding of the inspection requirements and procedures; and (iii) attitude and work ethic. Therefore, quality control procedures and periodic education are needed to reduce the inconsistencies and minimize the variations in the inspections between routine and in-depth safety inspections.

6. Estimation of Service Life of a Bridge

6.1 Service Life Expectancy Model

For the condition-based approach, a *HI* curve can be developed for a set of bridges. In general, the service life of a bridge T_s can be expressed as:

$$T_s = T_a + T_r \tag{8}$$

where T_a is the age of a bridge and T_r is the remaining service life of a bridge. When the condition rating of a bridge is located on the *HI* curve, the service life of the bridge is equivalent to the average service life (i.e., $T_s = T_{as}$; bridge 2 in Fig. 8). Hence, Eq. (8) becomes:

$$T_{as} = T_a + T_r \tag{9}$$

where T_{as} is the average service life of the bridge located on the *HI* curve. After substituting Eq. (9) into Eq. (3) and solving for T_r, the remaining service life (T_r) of an individual bridge can be obtained as follows:

$$T_r^i = T_{as}\left[1-\left(\frac{0.9-HI^i}{0.54}\right)^{\frac{1}{\beta}}\right] \tag{10}$$

where T_r^i is the remaining service life of the i^{th} bridge, T_{as} is the average service life, HI^i is the health index of the i^{th} bridge, and β is the slope of the *HI* curve. The values of T_{as} and β can be obtained through regression (see Fig. 3), and HI^i is the given information of the i^{th} bridge from routine inspection. Given information such as T_{as}, β, and HI^i, the remaining service life of the i^{th} bridge can be evaluated using Eq. (10).

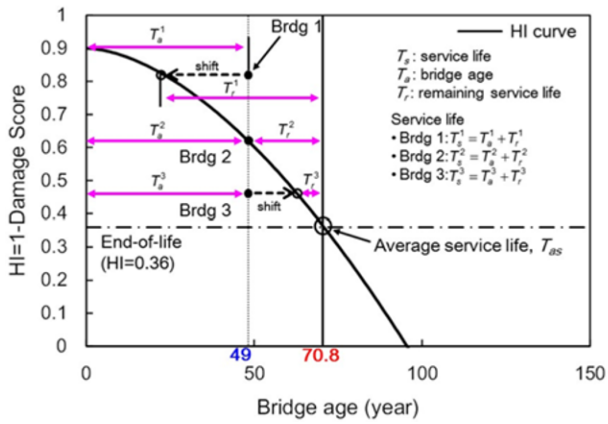

Fig. 8. Schematic Graph Describing the Remaining Service Life

Figure 8 shows the basic concept of estimating the remaining service life of an individual bridge. For simplicity, it is assumed that there are three cases of bridges with the same age. In the case where two bridges are not located on the *HI* curve, bridge 1 performs better than its age, whereas bridge 3 performs worse than its age. This indicates that the bridge located above the *HI* curve (bridge 1) has a longer remaining service life than its age, while the bridge located below the *HI* curve (bridge 3) has a shorter remaining service life than its age.

To evaluate the remaining service life of the bridges not located on the *HI* curve (bridges 1 and 3), the point is shifted horizontally to the *HI* curve so that the remaining service life is equal to the time from the point on the *HI* curve to the point of average service life, as shown in Fig. 8. For the bridge located on the *HI* curve (bridge 2), the remaining service life is equal to the time from the point on the *HI* curve to the point of the average service life. Since the proposed formula is independent of bridge age, the remaining service life of a bridge can be estimated using

Table 7. Examples of Estimating Expected Service Life of Bridges Having the Same Age (see Fig. 8)

	Health Index (HI^i)	Bridge age (T_a^i)	without *IRI**		with *IRI*	
			Remaining service life (T_r^i)	Service life ($T_s^i = T_a^i + T_r^i$)	Remaining service life (T_r^i)	Service life ($T_s^i = T_a^i + T_r^i$)
Bridge 1	0.881	49	$T_r^1 = 70.8\left[1-\left(\frac{0.9-0.881}{0.54}\right)^{\frac{1}{1.706}}\right] = 60.8$	109.8	$T_r^1 = 66.2 - 70.8\left(\frac{0.9-0.881}{0.54}\right)^{\frac{1}{1.706}} = 56.2$	105.2
Bridge 2	0.612		$T_r^1 = 70.8\left[1-\left(\frac{0.9-0.612}{0.54}\right)^{\frac{1}{1.706}}\right] = 21.8$	70.8	$T_r^1 = 66.2 - 70.8\left(\frac{0.9-0.612}{0.54}\right)^{\frac{1}{1.706}} = 17.2$	66.2
Bridge 3	0.442		$T_r^1 = 70.8\left[1-\left(\frac{0.9-0.442}{0.54}\right)^{\frac{1}{1.706}}\right] = 6.5$	55.5	$T_r^1 = 66.2 - 70.8\left(\frac{0.9-0.442}{0.54}\right)^{\frac{1}{1.706}} = 1.9$	50.9
Average	$T_s = \frac{1}{N}\sum_{i=1}^{N} T_s^i$			78.7		74.1

**IRI*: Inspection Reliability Index

the condition rating of a bridge only, regardless of the bridge age. Given *HI* of the i^{th} bridge, the proposed formula can evaluate the remaining service life after shifting the point horizontally to the *HI* curve. After estimating the remaining service life of the i^{th} bridge, the service life can then be evaluated using the following equation:

$$T_s^i = T_a^i + T_r^i \tag{11}$$

where T_s^i = Is the service life of the i^{th} bridge,
T_a^i = Is the age of the i^{th} bridge,
T_r^i = Is the remaining service life of the i^{th} bridge,

$$T_r^i = T_{as}\left[1-\left(\frac{0.9-HI^i}{0.54}\right)^{\frac{1}{\beta}}\right],$$

T_{as} and β are the average service life and the slope

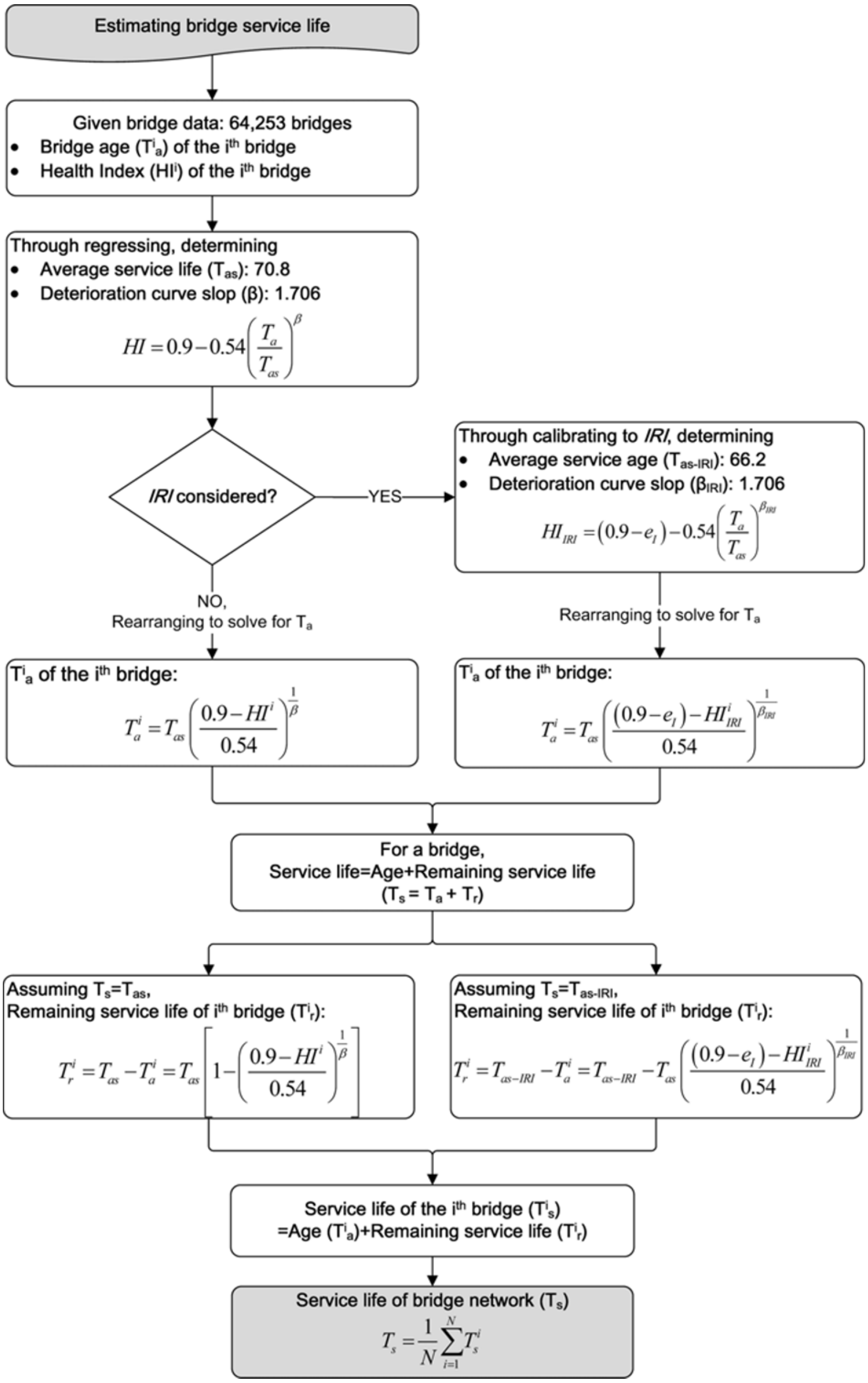

Fig. 9. Flow Chart for Estimating Service Life of a Bridge and a Bridge Network

of the *HI* curve respectively,

HI^i = is the health index of the i^{th} bridge.

6.2 Improving the Service Life Expectancy Model Accounting for Inspection Reliability

Equation (10) is proposed for the remaining service life of an individual bridge. If the *IRI* (Inspection Reliability Index) is known, it can be incorporated to improve the remaining service life expectancy model. The remaining service life expectancy model associated with *IRI* can be derived using a similar process to the derivation of the remaining service life expectancy model accounting *IRI*. The remaining service life expectancy model associated with the *IRI* is as follows:

$$T_r^i = T_{as-IRI} - T_{as}\left(\frac{(0.9 - e_I) - HI_{IRI}^i}{0.54}\right)^{\frac{1}{\beta_{IRI}}} \tag{12}$$

where T_r^i = is the remaining service life of the i^{th} bridge,

$T_{as\text{-}IRI}$ = is the average service associated with *IRI*,

T_{as} = Is the average service,

HI_{IRI}^i = Is the health index of the i^{th} bridge associated with *IRI*, $HI_{IRI}^i = HI^i - e_I$

β_{IRI} = is the slope of the HI curve associated with *IRI*,

e_I = is the inspection error.

Equation (12) delineates a method for quantifying the effects of the inspection reliability on the service life of an individual bridge. This new approach opens an avenue to incorporate bridge inspection reliability into the service life expectancy of an individual bridge and form a basis for a more rational approach to bridge management.

6.3 Examples of Evaluating Bridge Service Life

Table 7 presents examples of estimating the service life of bridges with the same age (see Fig. 8). The values of T_{as}, $T_{a\text{-}IRI}$, β, and β_{IRI} can be obtained through regression to routine inspection results and are required to estimate the service life. The values T_{as} = 70.8, $T_{a\text{-}IRI}$ = 66.2, and $\beta = \beta_{IRI}$ = 1.706 are used as examples. The service life expectancy estimation methodology presented in Fig. 9 applies to an individual bridge and a bridge network depending on the availability of *IRI*.

7. Conclusions

This paper presented the development of a service life expectancy model associated with *IRI* (Inspection Reliability Index) for highway bridges in South Korea. Firstly, end-of-life was defined to determine the service life, and then the life expectancy model was developed using a non-linear regression model. The average service life based on 10-year routine inspection data was 70.8 years under current maintenance practices. The *IRI* was also developed to evaluate the inspection accuracy of routine inspection with respect to *HI* ratings of the in-depth safety inspection. In the evaluation of the *IRI*, *HI* ratings obtained using in-depth safety inspection procedures were assumed to be "true" values. The *IRI* was evaluated as 42%, which indicated that the difference in the *HI* rating obtained by routine inspection procedures with respect to in-depth safety inspection procedures was 0.058 on average. A service life expectancy model was developed by a non-linear regression model. Since the censored bridge data were used to develop the life expectancy model, the inspection accuracy among many factors such as material types or structural types was considered. The service life expectancy model adjusted by the *IRI* was then proposed to consider the effect of inspection accuracy on estimates of bridge service life expectancy. In further study, when various factors are taken into consideration in developing life expectancy model, the life expectancy model will be a more effective tool for developing bridge maintenance programs and assessing lifecycle costs.

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