Article

Prediction of Remaining Life for Bridge Decks Considering Deterioration Factors and Propose of Prioritization Process for Bridge Deck Maintenance

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Abstract: Aged highway bridges have become substantially prevalent in recent years. Moreover, combined deterioration, caused by using deicing agents in winter, has led to increased bridge maintenance costs. Accordingly, to extend the service life of bridge decks, this study utilized actual inspection data and major deterioration factors to derive the remaining service life of bridge decks. Based on this study, the following three factors are selected: deicing agent exposure grade, pavement condition state, and surface improvement status. Performance degradation curves were derived for 11 cases that considered the representative three deterioration factors, and the performance degradation of decks was examined for each deterioration factor. Additionally, a process to determine maintenance priorities, using the current condition of highway bridges and the deterioration factors of individual bridges, was proposed. The maintenance demand was predicted based on the end of deck life, which indicated that the demand for deck replacement will sharply increase in 15 years, and that the decks of more than 2000 bridges will reach the end of life in 40 years. Furthermore, this paper proposes a process for prioritizing the maintenance of approximately 9000 highway bridge decks. By applying the prioritization process for bridge deck maintenance to the bridge deck, not only can the life of the bridge deck be extended, but also environmental pollution can be minimized. Additionally, an optimizing design for bridge decks, by considering the remaining life and deterioration factors, can be possible. Therefore, it is expected that the sustainability of the bridge deck can be accomplished.

Keywords: bridge decks; maintenance; deterioration factors; remaining service life

1. Introduction

In recent years, aged highway bridges have become prevalent in South Korea, and combined deterioration, caused by the use of deicing agents in winter, has led to increased bridge maintenance costs, as shown in Figures 1 and 2. Due to the aging of bridges, and the increasing use of deicing agents, the service life of bridge decks may be reduced, and also environmental pollution may be caused due to repair or improvement works. In the worst case, if an improvement work of the deck happens, a lot of construction costs, environmental pollution, such as noise and dust, and traffic jams may occur. Bridge decks are bridge members that directly transmit vehicle loads to other members, and are typically designed for a maximum load of 423.7 kN. Their durability degrades faster than that of other members because of the damage and deterioration caused by direct exposure to physicochemical deterioration factors [1].
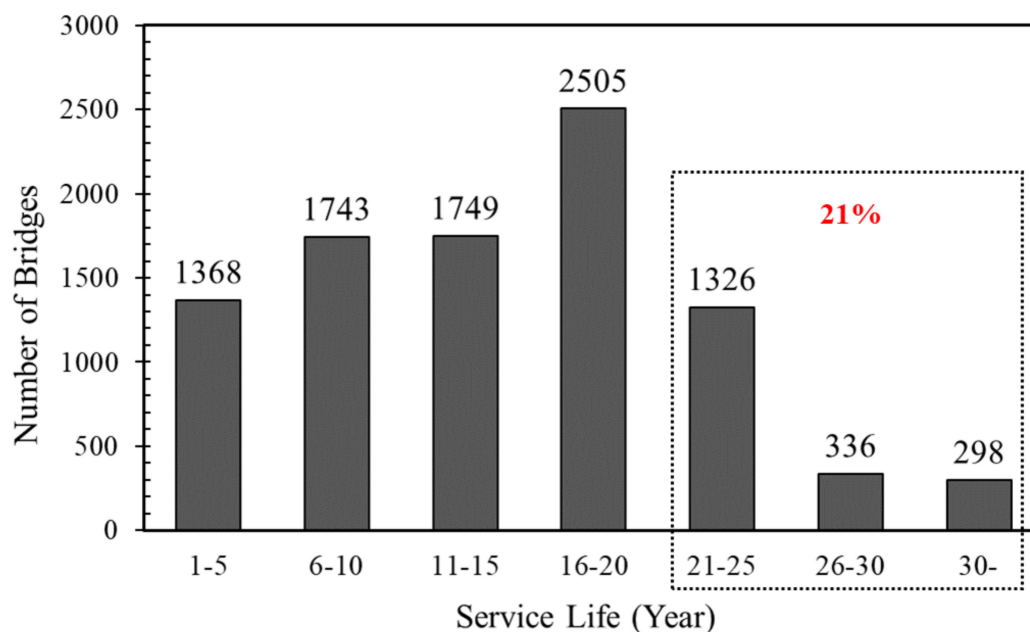
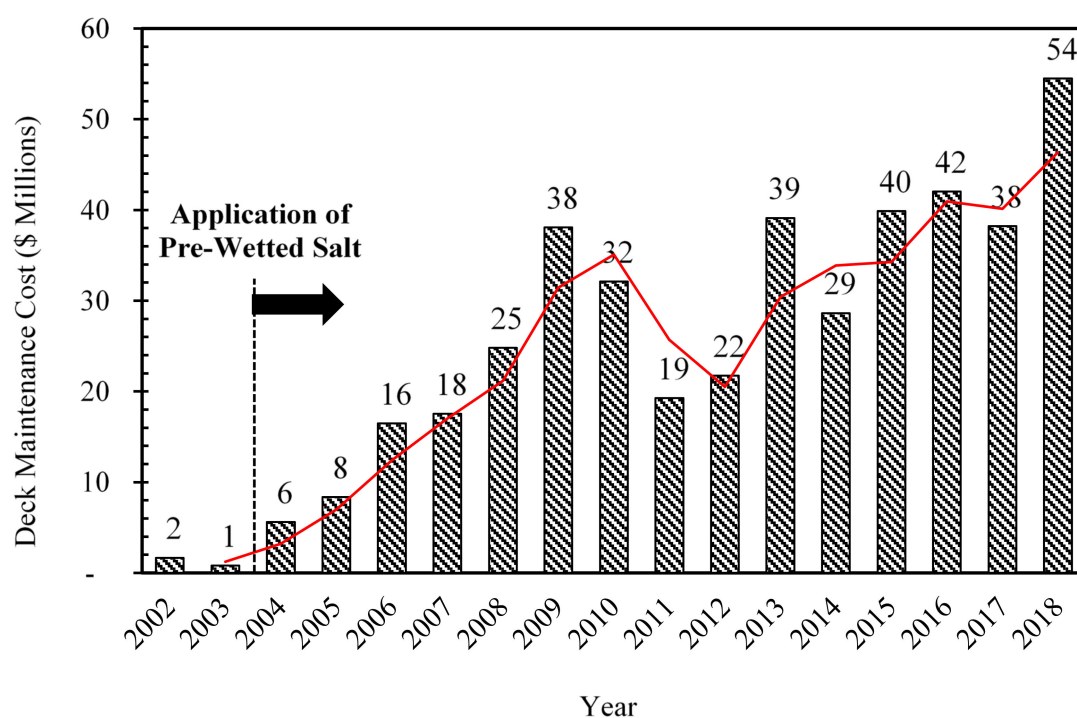**Figure 1.** Current service lives of highway bridges in South Korea.

Figure 2. Maintenance cost for highway bridge decks in South Korea.

According to domestic facility maintenance laws, the management entities of bridges must regularly perform safety inspections and diagnoses, through which the condition of each member is graded based on condition evaluation criteria [2]. The condition is evaluated using one of five grades from A to E, and the interpretation of each grade is provided in Table 1. However, the pavement installed on the top surface of bridge decks makes it difficult to evaluate top surfaces; thus, the conditions of the bottom surfaces are evaluated instead. Furthermore, most inspections rely on rapid visual surveys that do not provide accurate assessments of the deck condition [3–6]. Therefore, as shown in Figure 3, even decks that are evaluated to be in good condition often exhibit considerable deterioration, which frequently continues when appropriate measures are not taken.

Table 1. Criteria for Evaluating Condition State and Damage Rate (KISTEC, 2019).

Condition State	Description	Damage Index	Damage Range
A	Excellent condition	0.1	$0 \leq X < 0.13$
B	Minor problems in secondary members Needs repair works to increase durability	0.2	$0.13 \leq X < 0.26$
C	Minor problems in primary members and extensive problems in secondary members Needs repair works to improve performance.	0.4	$0.26 \leq X < 0.49$
D	Extensive problems in primary members Needs reinforcement works to ensure structural safety Road closure considered	0.7	$0.49 \leq X < 0.79$
E	Critical or failure condition. Close the bridge Needs reinforcement or rebuilding	1.0	$0.79 \leq X$

(a)

(b)

Figure 3. Deterioration of the top and bottom surfaces of the deck at the same location. (**a**) Evaluated good condition (Condition State B); (**b**) Severe Deterioration of Top Surface of the Deck.

To address increasing concerns related to bridge deck deterioration because of the continuous use of deicing agents [7], many researchers have attempted to identify the mechanism of deck deterioration owing to deicing salt. Internal and external cracks in bridge decks are caused by dry shrinkage, external

loads, corrosion, moisture, and chloride ions which penetrate through these cracks to corrode the steel reinforcement inside the concrete, as shown in Figure 4a,b. This process degrades the durability of the deck and causes structural damage to the bridge [8]. Corrosion of the deck's top steel reinforcement leads to heaving of the bond interface between the pavement and the deck, thus continuously damaging the bridge surface; in contrast, corrosion in the bottom steel reinforcement degrades the load-carrying capacity of the decks, thus reducing safety [9]. In particular, if a bridge deck deteriorates, water leakage and stagnant water generated in the top surface continuously corrodes the internal steel reinforcement, thereby penetrating the material and damaging the bottom surface, as shown in Figure 4c,d. Corrosion in the bottom steel reinforcement requires full-depth repair or partial replacement of the deck, which is extremely costly and time-consuming [10,11]. Currently, decisions for the maintenance of highway bridge decks are based on their condition states. As a result, it is difficult to make appropriate decisions for maintenance considering the performance degradation of the decks based only on the current condition states, which evaluates only the bottom surface condition [10].
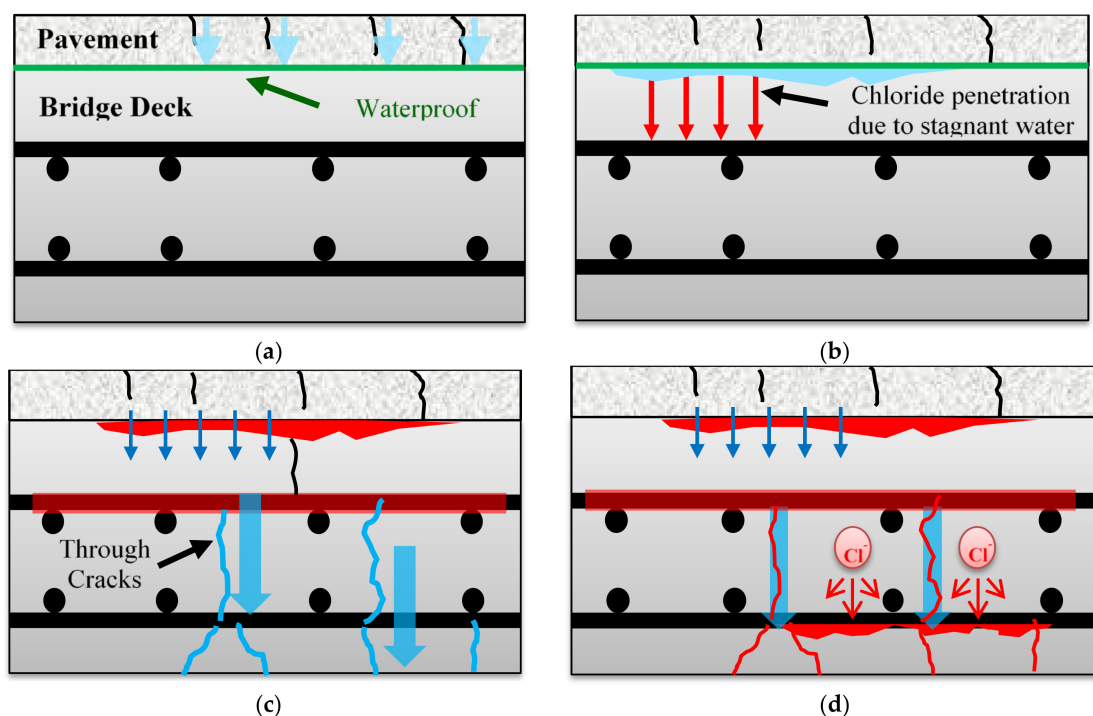

Figure 4. Bridge deck composition and deterioration mechanism. (**a**) Rainwater penetration due to initial cracks and damage to the waterproof layer; (**b**) Chloride penetration into the deck top surface due to the stagnant water with salt; (**c**) Water leakage to the deck bottom surface due to crack propagation; (**d**) Corrosion of steel reinforcement at the bottom and damage to the deck bottom surface.

Researchers have recently studied nondestructive investigation techniques and the prediction of the deterioration condition of decks in relation to bridge deck maintenance. First, nondestructive investigation techniques, such as ground-penetrating radar (GPR), have been used to examine the deterioration of the top surface of decks for maintenance [12,13]. However, owing to equipment operation limitations and reduced reliability based on the pavement material, they cannot serve as fundamental solutions [10,14]. Theoretical studies have also been conducted on the development of evaluation techniques for bridge deck aging, improvement of deck repair and reinforcement methods, and factors affecting the durability of decks [15]; in addition, studies that collected and analyzed information on aging bridges to propose deterioration models and predict demand for the replacement of aged bridge decks have also been conducted [16–19]. Comparative analysis of large numbers of bridges enables a decision-making in bridge design, construction, and maintenance [20–24].

However, these studies did not comprehensively examine the various factors that affect the performance degradation of decks and limitations in the quantity of maintenance data.

To address these problems, this study incorporated over 120,000 points of actual condition states data accumulated over 20 years of inspections and diagnoses to derive deck performance degradation curves. It proposed a process for prioritizing the maintenance of actual highway bridge decks by calculating their remaining life, considering various deterioration factors that affect the performance degradation of the decks.

2. Research Method

This study followed the research method shown in Figure 5 to predict the remaining life of the decks considering their deterioration factors and present maintenance priorities considering the current condition states of actual highway bridges. In order to predict the service life of the bridge deck and derive the priority for maintenance, the following five steps of research were conducted. In the first step, the current state evaluation data of 120,000 actual inspection data is analyzed, and in the second step, the deterioration factor is determined by considering various factors, such as deicing agent exposure grade, pavement condition states, and so on. In the third step, the deterioration curve considering the deterioration factor is derived by applying a simple regression analysis on the 120,000 actual inspection data, and in the fourth step, the remaining life of the bridge deck is predicted. In the last step, a procedure for selecting the priority of maintenance of the bridge deck is suggested by considering the results performed in the previous steps.
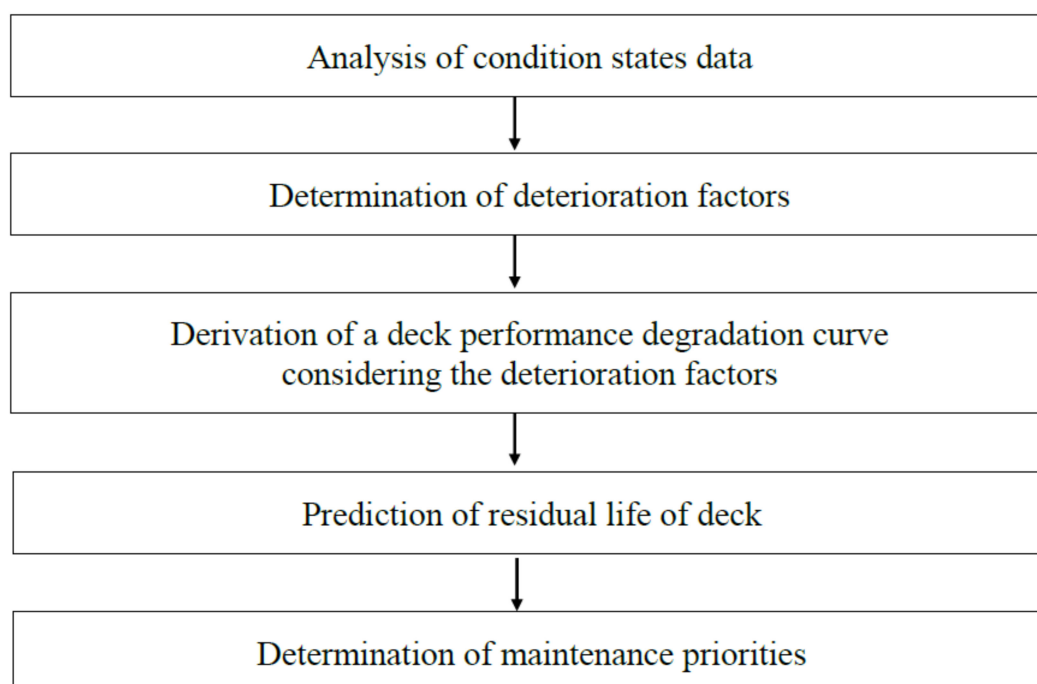

Figure 5. Method of conducting research.

The existing maintenance of the bridge deck has not been able to guarantee economy and efficiency because the factors affecting the performance degradation have not been considered and have been carried out uniformly. By applying the results of this study, it is possible to perform timely and effective maintenance of bridge decks in different environments. However, additional manpower, analysis work, and budget may be incurred accordingly, but these ancillary contents may be offset by the life extension effect obtained by applying the bridge deck maintenance method considering the deterioration factor. The authors have added this comment to Chapter 2 Research Method.

3. Analysis of Condition States Data

Using 9443 highway bridges for the analysis, this study collected and analyzed 120,000 points of maintenance data related to bridge condition states and deterioration factors, obtained from 2000 to 2019. The data were accumulated in the Highway Bridge Management System (HBMS) of the Korea Expressway Corporation (EX). In addition, the performance degradation curves were derived by converting the condition states (A to E) into damage indices, as shown in Table 1.

South Korea began to construct highway bridges in the 1960s, and these bridges increased in quantity from the 1990s and peaked in the 2000s. Their maximum service life is 51 years, while the service lives of most bridges are less than 30 years. At the time of the survey, condition states A and B accounted for 97% of all decks, indicating that the decks were maintained with a rating target of B (Figures 6 and 7).
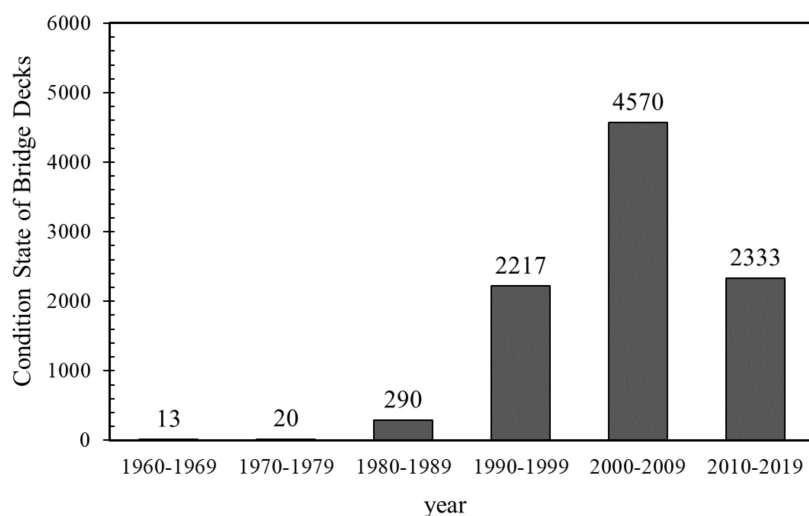

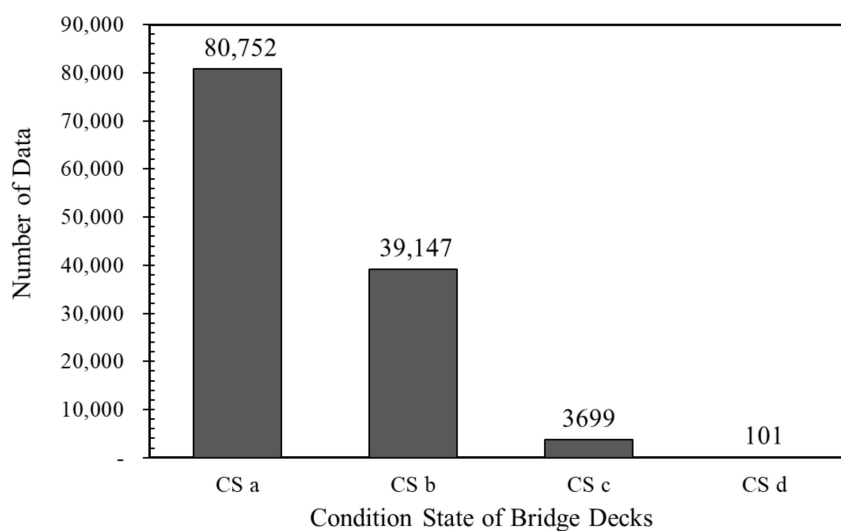**Figure 6.** Distribution of highway bridges according to construction year.

Figure 7. Distribution of condition states of highway bridge decks.

4. Determination of Deterioration Factors

The durability of bridge decks is degraded by not only the defects occurring in the construction stage, such as initial cracks and material separation, but also by various factors that occur while they are being used, such as chloride attack, snowfall, freezing and thawing, pavement damage condition, traffic volume, bridge deck pavement type, and maintenance quality [25]. This study examined representative

factors that can describe these various factors, and the following three factors that can reflect combined deterioration and damage were selected and reflected in the analysis: (1) deicing agent exposure grade (chloride attack, snowfall, and freezing and thawing), (2) pavement condition state (bridge deck pavement type, traffic volume, and pavement damage condition), and (3) surface improvement status (bridge deck pavement type and maintenance quality).

4.1. Deicing Agent Exposure Grade

Water leakage and stagnant water with chlorides that penetrate the deck from the pavement surface are key causes of deterioration; hence, the chloride environment is closely related to the performance degradation of decks [1,26,27]. EX classified the deicing agent exposure grade of highway bridges into four classes based on the regional snowfall data of the Korea Meteorological Administration (30-year statistical data) in Table 2 and Figure 8. They range from Class-1, with the smallest amount of deicing agents used, to Class-4, with the largest amount of deicing agents used [28]. This study selected the deicing agent exposure grade as a deterioration factor to simultaneously consider the winter environment and the amount of chlorides used for bridges by region.

Table 2. Deicing agent exposure grade for highways (EX, 2016).

| ExposureGrade	Snowfall(mm)	Target Regions [Metropolitan Cities and Provinces (Cities and Counties)]
Class-1	<150	Busan, Daegu, Ulsan, Jeonnam (Gwangyang, Yeosu, Namhae, Goheung, and Wando) Gyeongbuk (Yeongdeok, Cheongsong, Pohang, Yeongcheon, Gyeongsan, Cheongdo, Chilgok, Goryeong, and Gyeongju) Gyongnam (Changnyeong, Milyang, Euyryeong, Yangsan, Haman, Jinju, Changwon, Gimhae, Hadong, Sacheon, Goseong, Geoje, Tongyeong, Jinhae, and Masan)
Class-2	150–300	Incheon, Gyeonggi (Gimpo, Bucheon, Siheung, and Ganghwa), Gyeongbuk (Yeongju, Uljin, Yecheon, Andong, Yeongyang, Euyseong, Gumi, Gunwi, and Seongju) Gyeongnam (Hancheon and Sancheong), Jeonnam (Suncheon, Boseong, Jangheung, Gangjin, Haenam, and Jindo)
Class-3	300–600	Seoul, Daejeon, Gyeonggi (all regions except Gimpo, Bucheon, and Siheung), Gangwon (Cheolwon, Hwacheon, Yanggu, Inje, Chuncheon, Hoengseong, Wonju, Yeongwol, and Donghae), All regions in Chungnam and Chungbuk, Gyeongbuk (Bonghwa, Mungyeong, Sangju, and Kimcheon), Gyeongnam (Geochang and Hanyang) Jeonbuk (Gunsan, Iksan, Wanju, Jeonju, Jinan, Muju, and Namwon), Jeonnam (Hampyeong, Muan, Mokpo, Yeongam, Naju, Hwasun, Gokseong, Gurye, and sinan)
Class-4	>600	Gwangju, Jeonnam (Yeonggwang, Jangseong, and Damyang), Jeonbuk (Gimje, Buan, Jeongeup, Imsil, Jangsu, Gochang, and Sunchang), Gangwon (Goseong, Sokcho, Yangyang, Gangneung, Pyeongchang, Hongcheon, Jeongseon, Samcheok, and Taebaek)
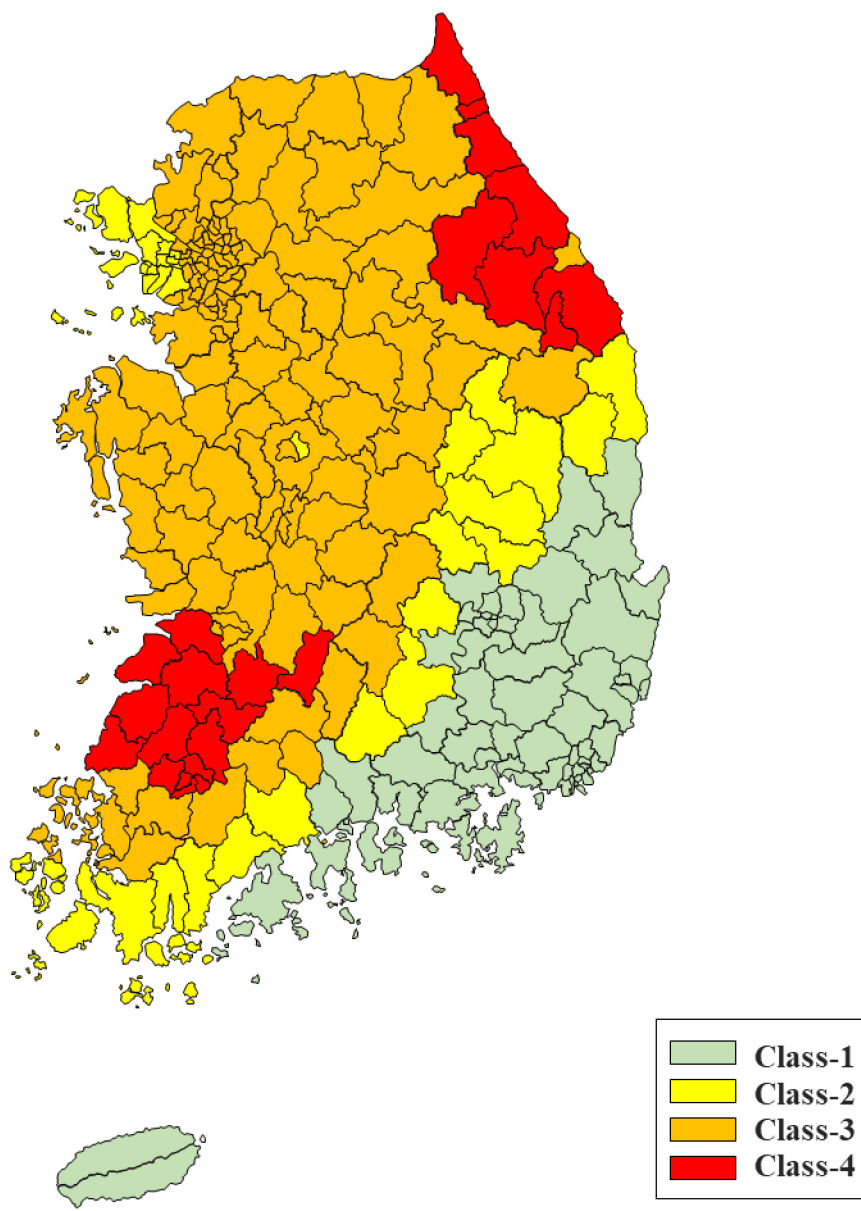
Figure 8. Geographic distribution of EX-defined exposure class.

4.2. Pavement Condition State

The bridge deck pavement is a type of wearing layer that protects the deck. If the pavement and waterproof layer are damaged, the deck is subjected to deterioration due to water leakage and stagnant water. Therefore, pavement damage is closely related to deck condition [29]. In addition, as many factors affect the deterioration of pavements and decks, such as the traffic volume, pavement materials, and waterproof layer type, this study selected the pavement condition state as an important deterioration factor, which represents the current condition by simultaneously reflecting various damage and deterioration factors. EX classified the pavement condition state from a to d (a: excellent condition, b: Needs repair works to increase durability, c: needs reinforcement works, d: critical or failure condition) for their maintenance.

4.3. Re-Pavement or Deck Improvement Status (Surface Improvement Status)

In general, when the performance of bridge members is degraded due to damage or deterioration, repair or reinforcement is performed to recover or maintain performance. However, when complete repair or improvement of bridge deck pavement is performed due to deterioration, such as the corrosion of steel reinforcement in the deck, re-deterioration often occurs due to leakage in the bond interface, incomplete repair of the deteriorated parts, inadequate anticorrosive treatment of the steel reinforcement, etc. [30]. In fact, 951 bridges in this study, corresponding to approximately 10% of the 9443 highway bridges, were completely improved in 16 years, as shown in Figure 9. These bridges were subjected to a second improvement before six years, on average, indicating that the maintenance period decreases for bridges that underwent re-pavement or deck improvement to recover performance [10]. Therefore, the surface improvement status was determined as an important factor for the performance degradation of decks.
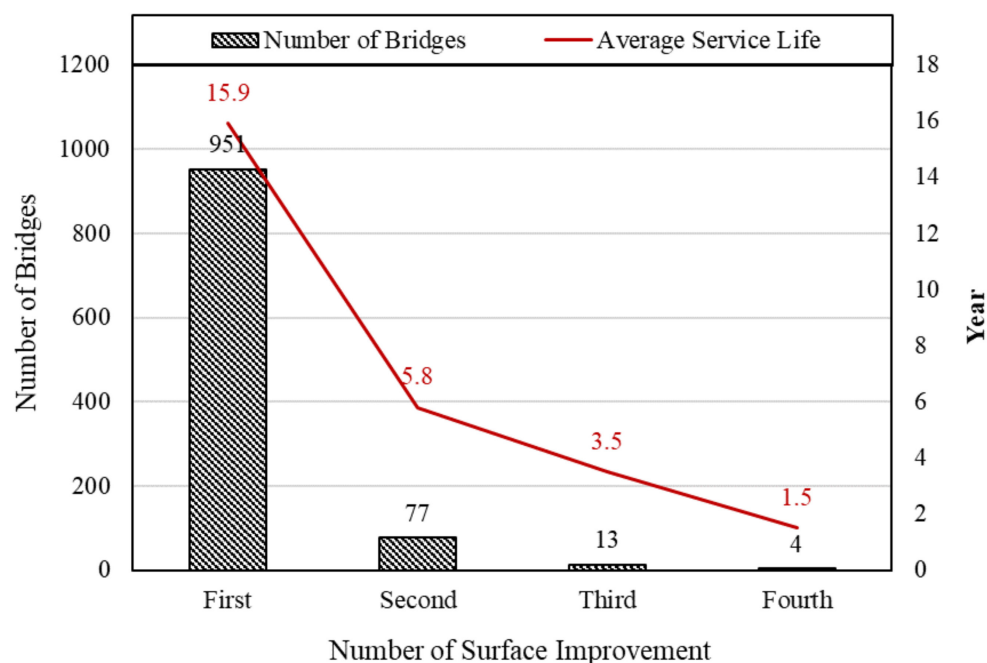

Figure 9. Surface improvement status data analysis results.

5. Derivation of Deck Performance Degradation Curves Considering the Deterioration Factors

In this study, the following three deterioration factors were selected to analyze the performance degradation of decks: (1) deicing agent exposure grade, (2) pavement condition state, and (3) surface improvement status. Considering the cases of each factor and the combined influence, the performance degradation was analyzed according to the service life for 11 cases, as shown in Table 3, using 120,000 points of maintenance data (Figure 10).
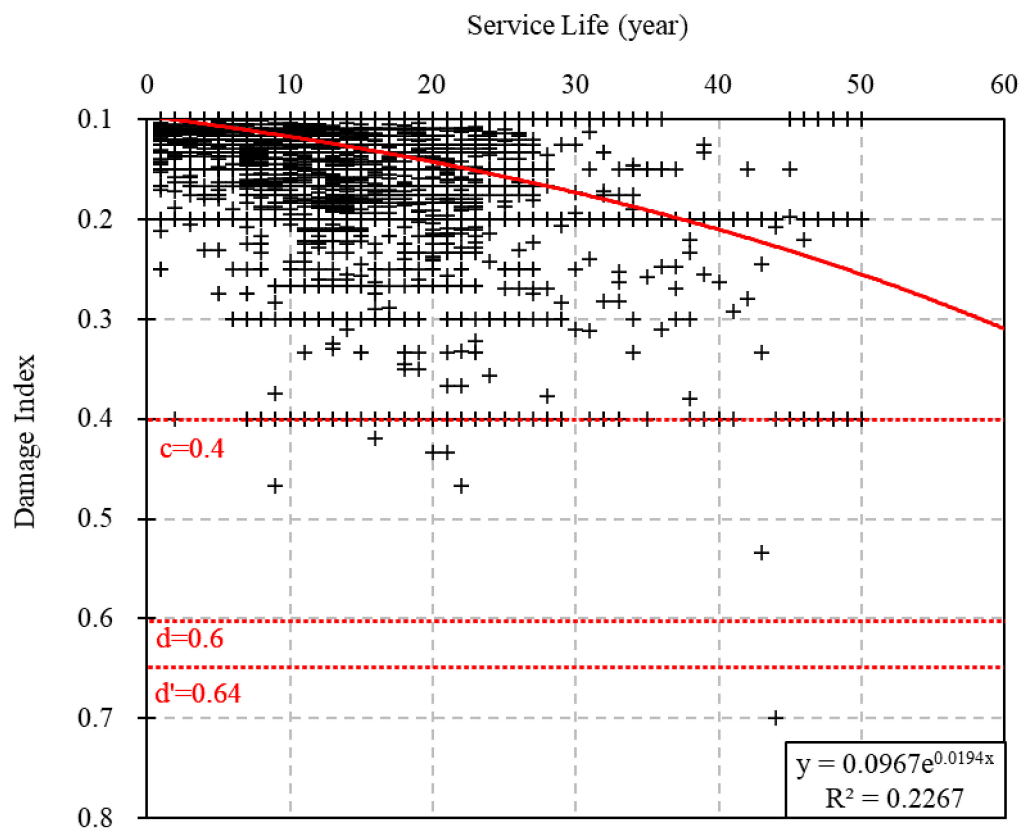
Table 3. Case numbers of bridge deck deterioration factors.

Deterioration Factors	Analysis Cases	Case NO.
All Data	All	1
Deicing agent exposure grade	Class-1	2
	Class-2	3
	Class-3	4
	Class-4	5
Pavement condition state (CS)	CS a	6
	CS b	7
	CS c	8
	CS d	9
Surface improvement status	Unimproved	10
	Improved	11
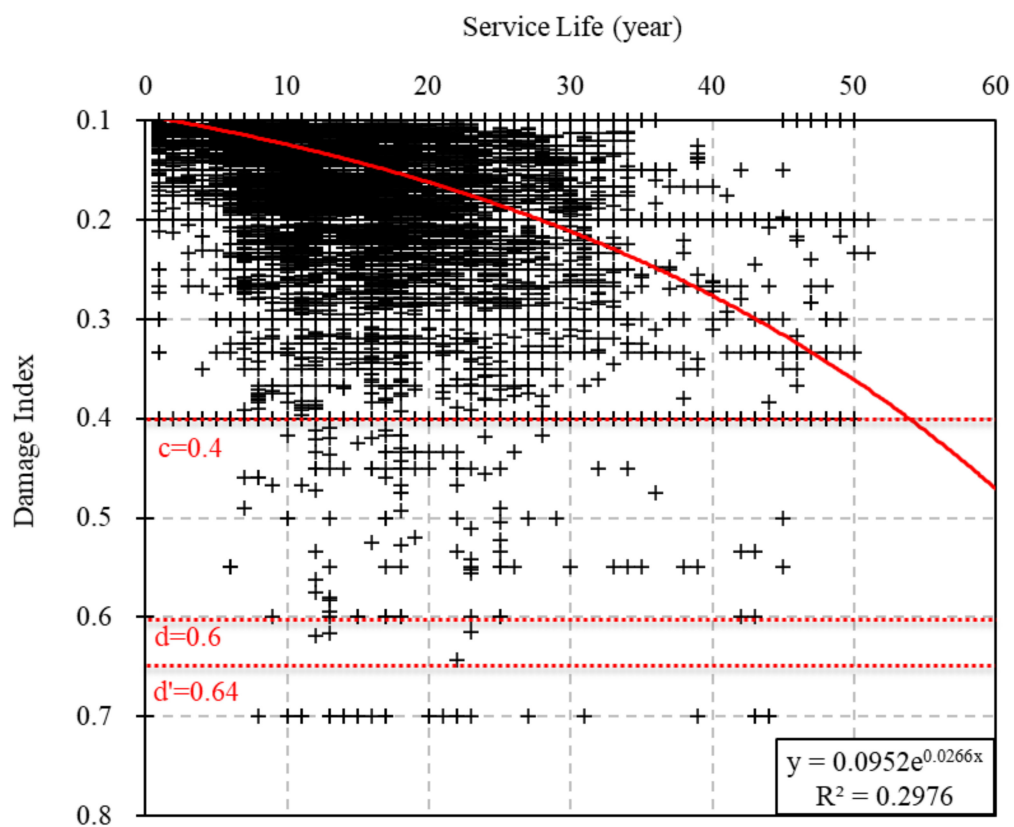
(a)

Figure 10. *Cont*.

(b)
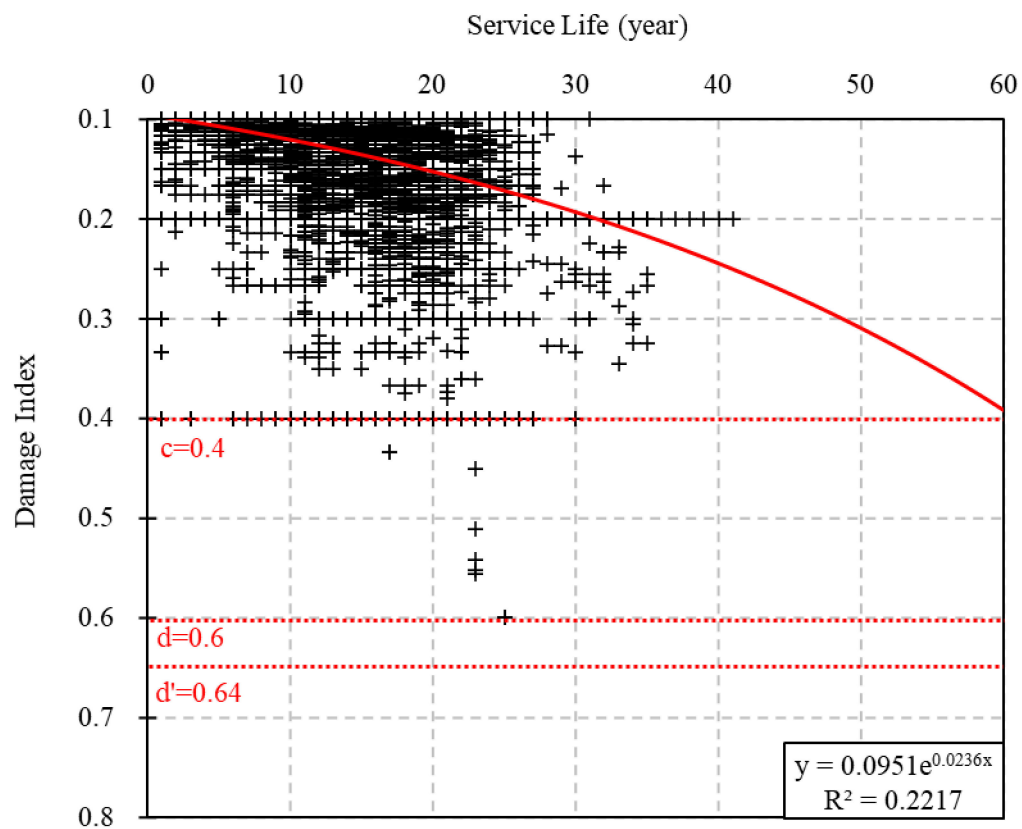
(c)

Figure 10. *Cont.*
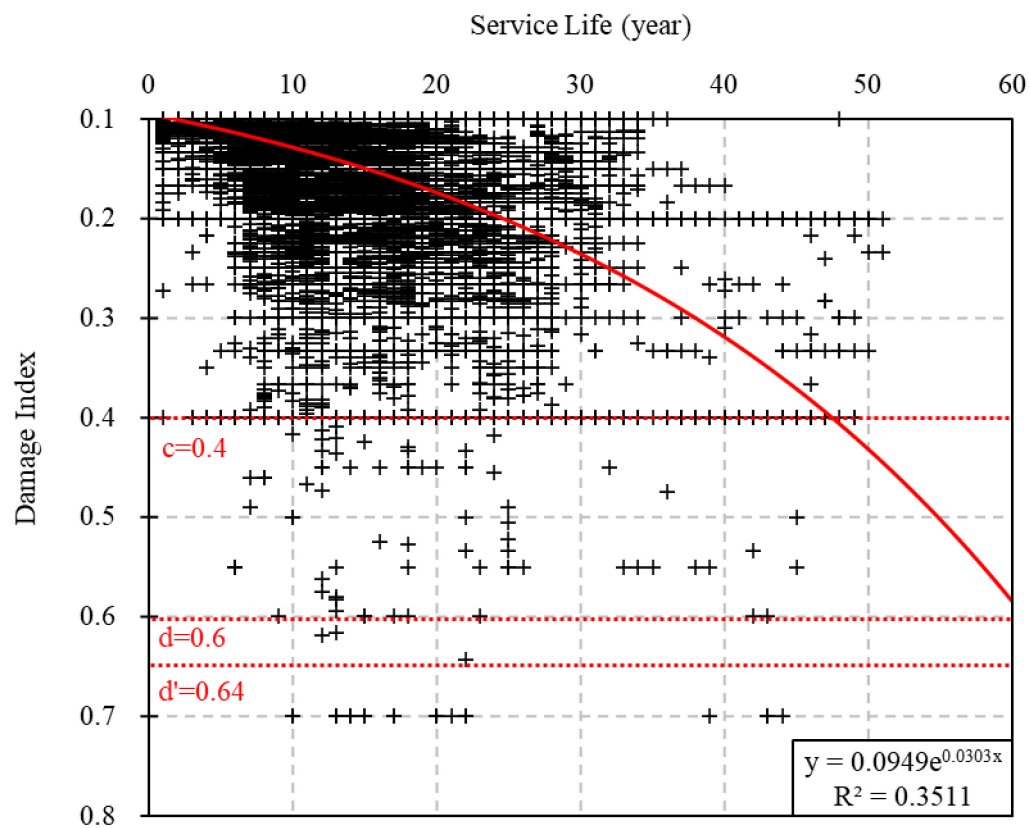
(d)
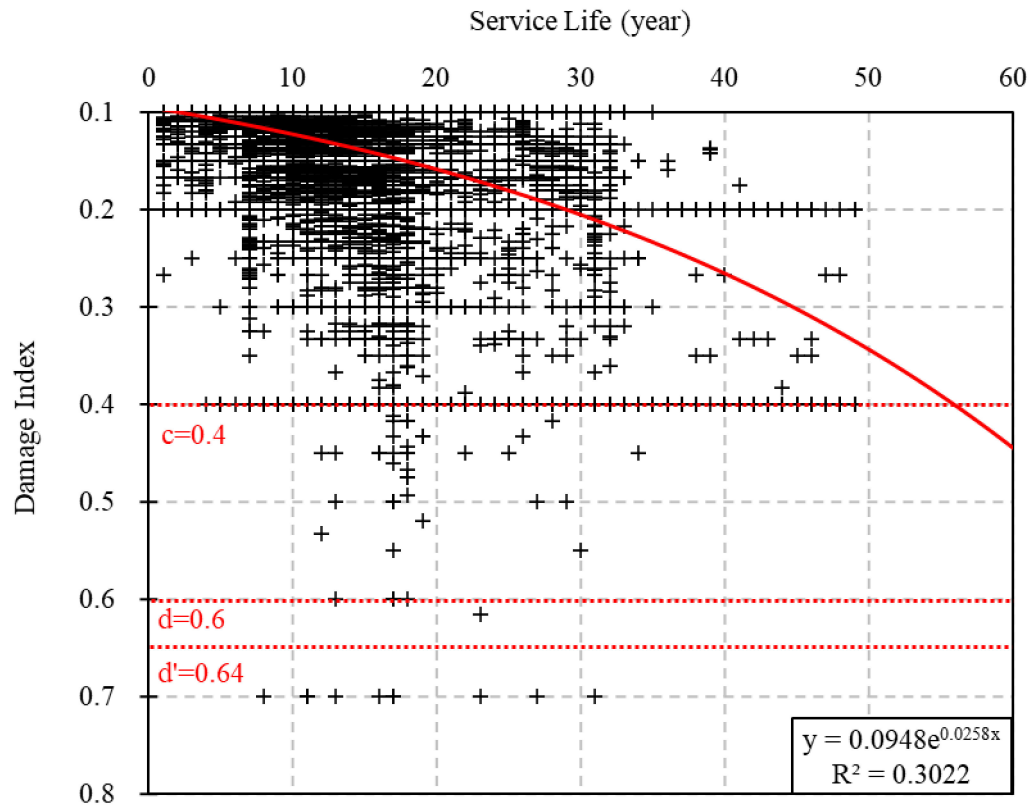
(e)

Figure 10. *Cont.*
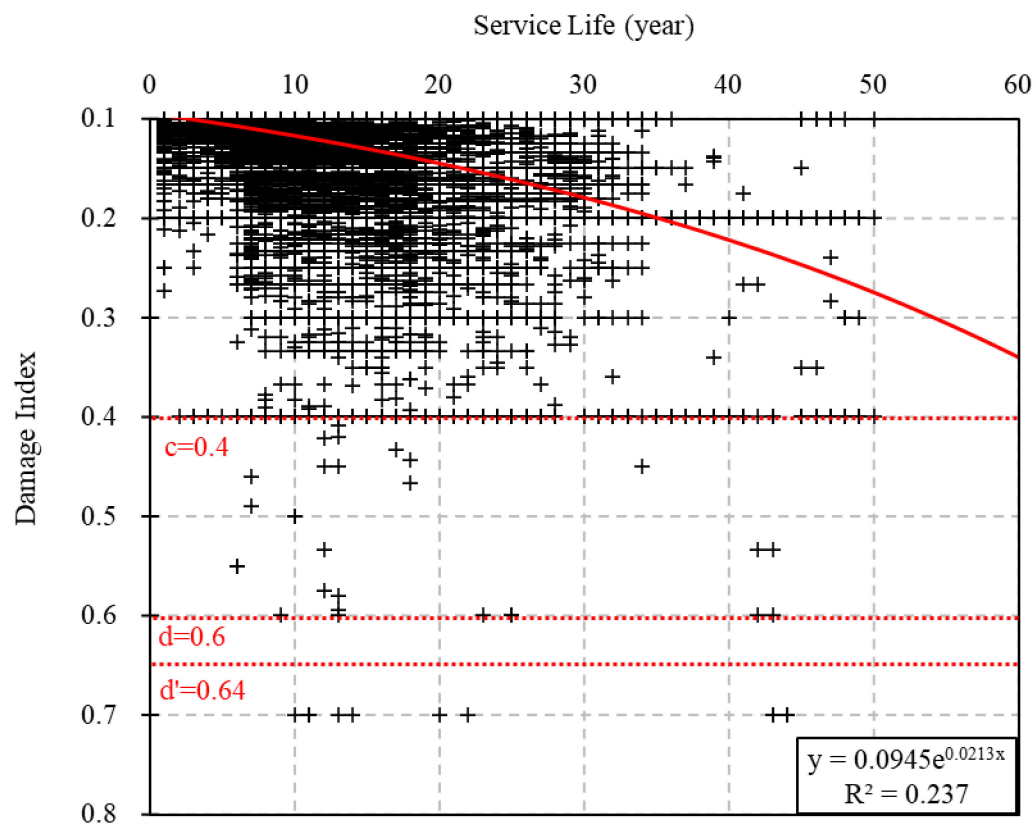
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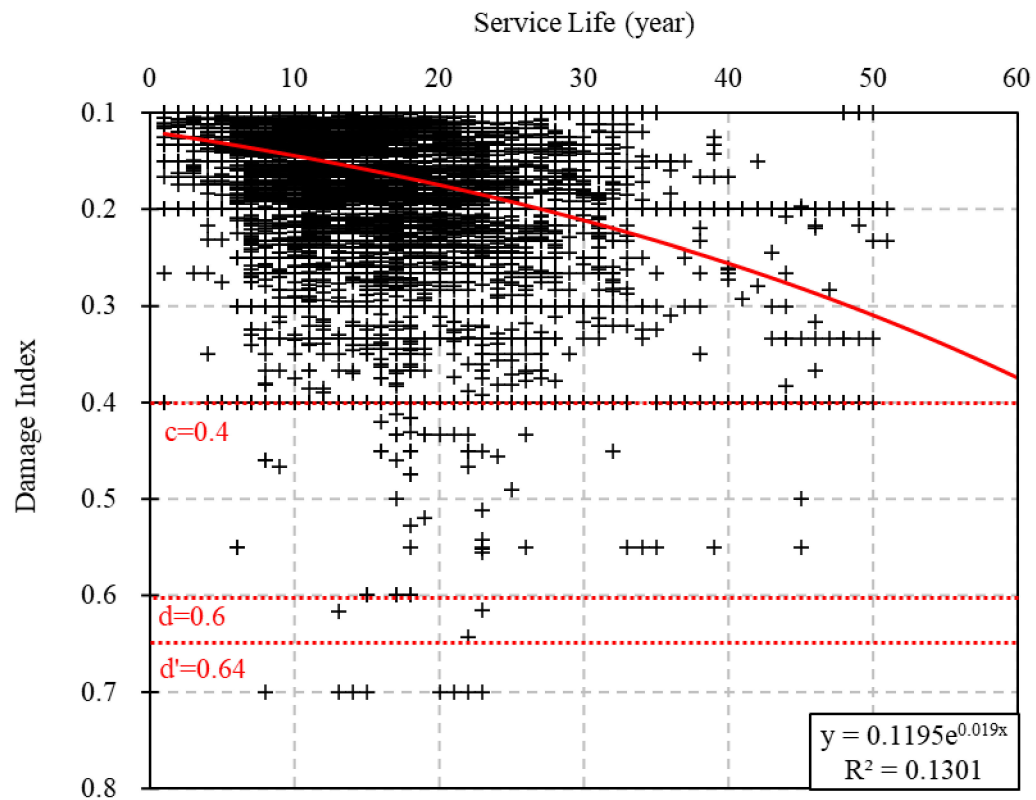
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Figure 10. *Cont.*
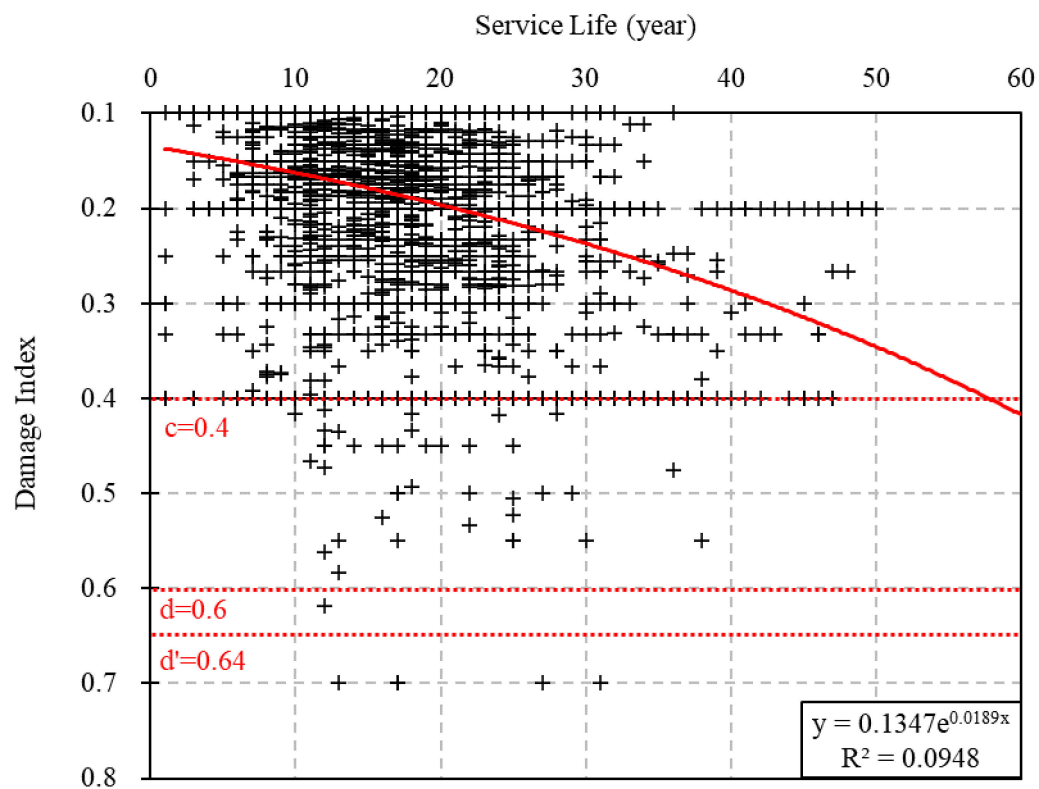
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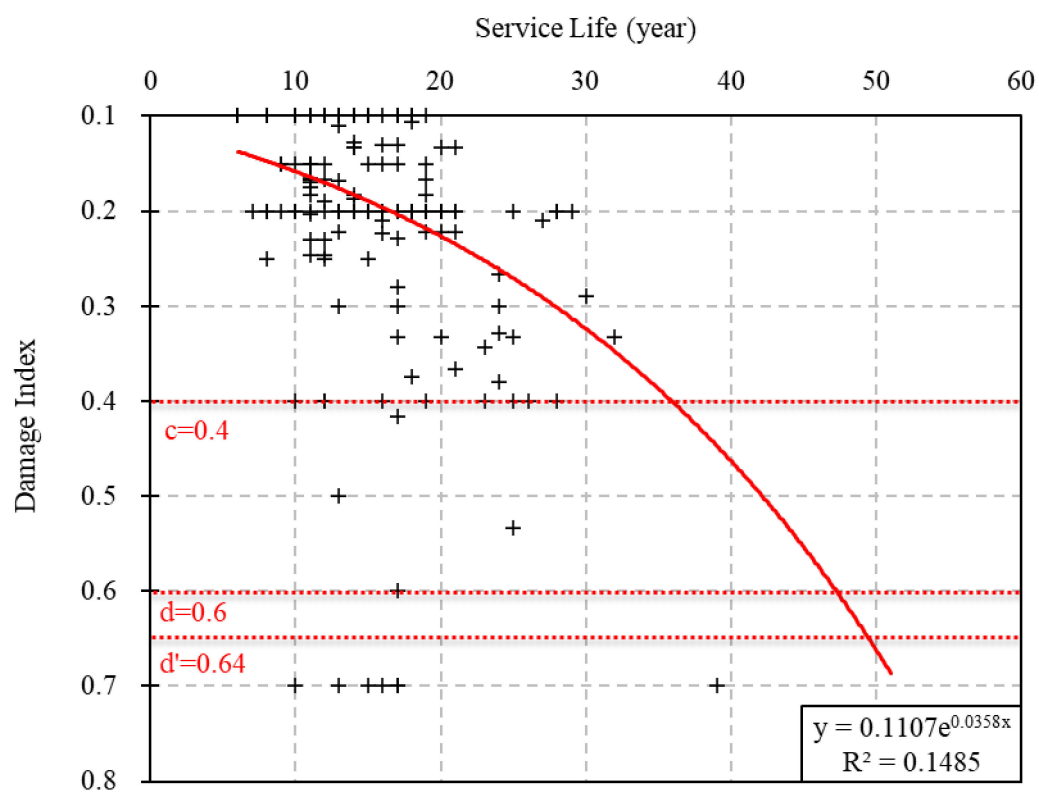
(i)

Figure 10. *Cont.*
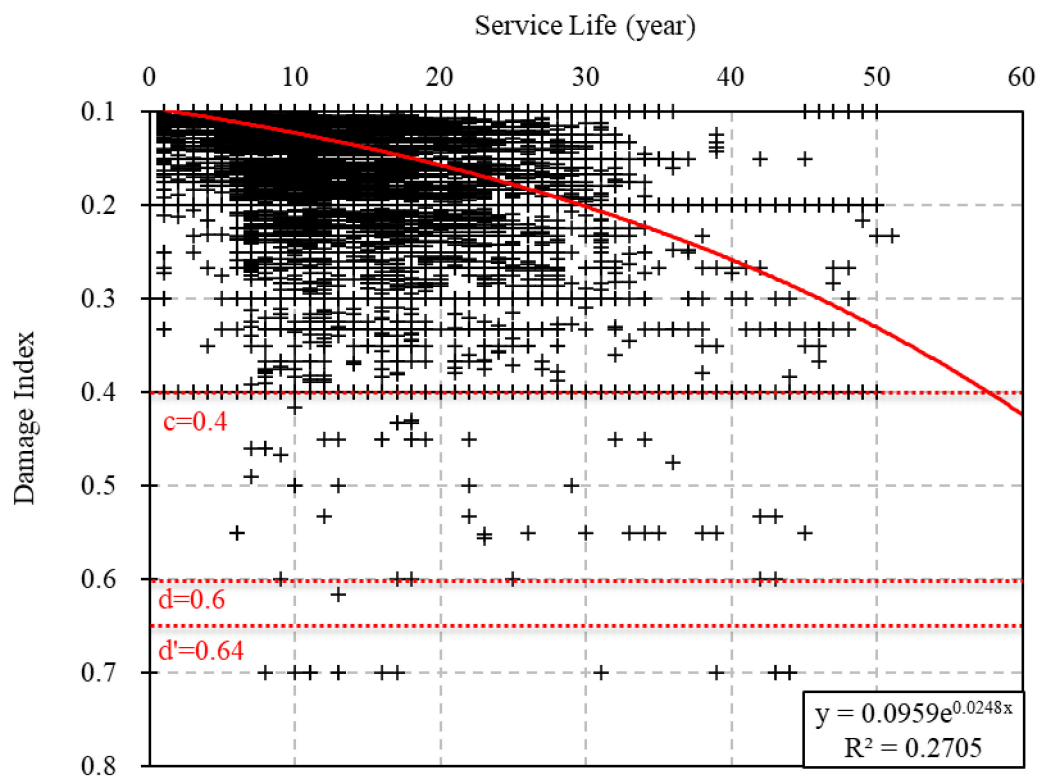
(j)
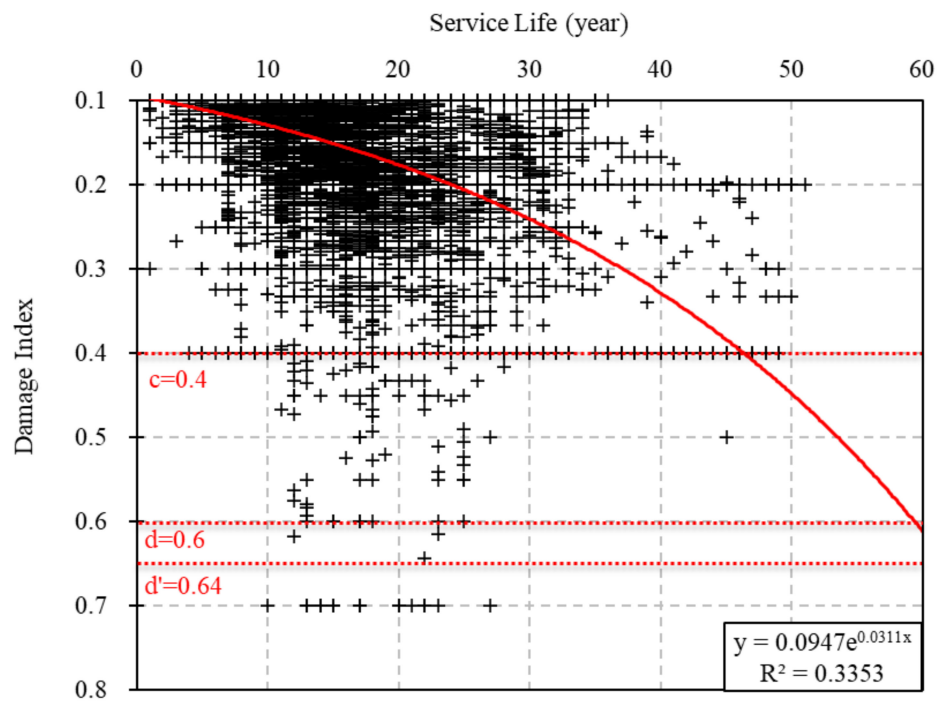
(k)

Figure 10. Deck performance degradation curves. (**a**) Case No.1 (All); (**b**) Case No.2 (Class-1); (**c**) Case No.3 (Class-2); (**d**) Case No.4 (Class-3); (**e**) Case No.5 (Class-4); (**f**) Case No.6 (Pavement CS a); (**g**) Case No.7 (Pavement CS b); (**h**) Case No.8 (Pavement CS c); (**i**) Case No.9 (Pavement CS d); (**j**) Case No.10 (Unimproved); (**k**) Case No.11 (Improved).

There are two representative techniques for predicting the remaining life of the bridge deck: (1) regression analysis and (2) survivability model [31]. In this paper, rather than propose a new technique for estimating the service life of bridge decks, deriving of maintenance procedure considering various factors that affect the service life of bridge decks is the main purpose by applying a simple regression analysis on the 120,000 actual inspection data. The simple regression analysis is one of representative regression analysis for predicting the remaining life of the bridge [1,32–34].

In this study, the remaining service life of the decks were derived using the condition states (damage index) of bridge decks as shown in Figure 10; the remaining life of the deck is shown separately for each case. In order to confirm this aspect more clearly, the remaining life of the bridge deck for each deterioration factor was redesigned, as shown in Figure 11, and it was confirmed that each deterioration factor has a certain effect on the performance degradation of the decks and reduces the remaining life. Among the three deterioration factors, the pavement condition grade was found to have the greatest effect (up to 41 years reduced) on the remaining life of the deck. The detailed analyses results are described in the following sections.
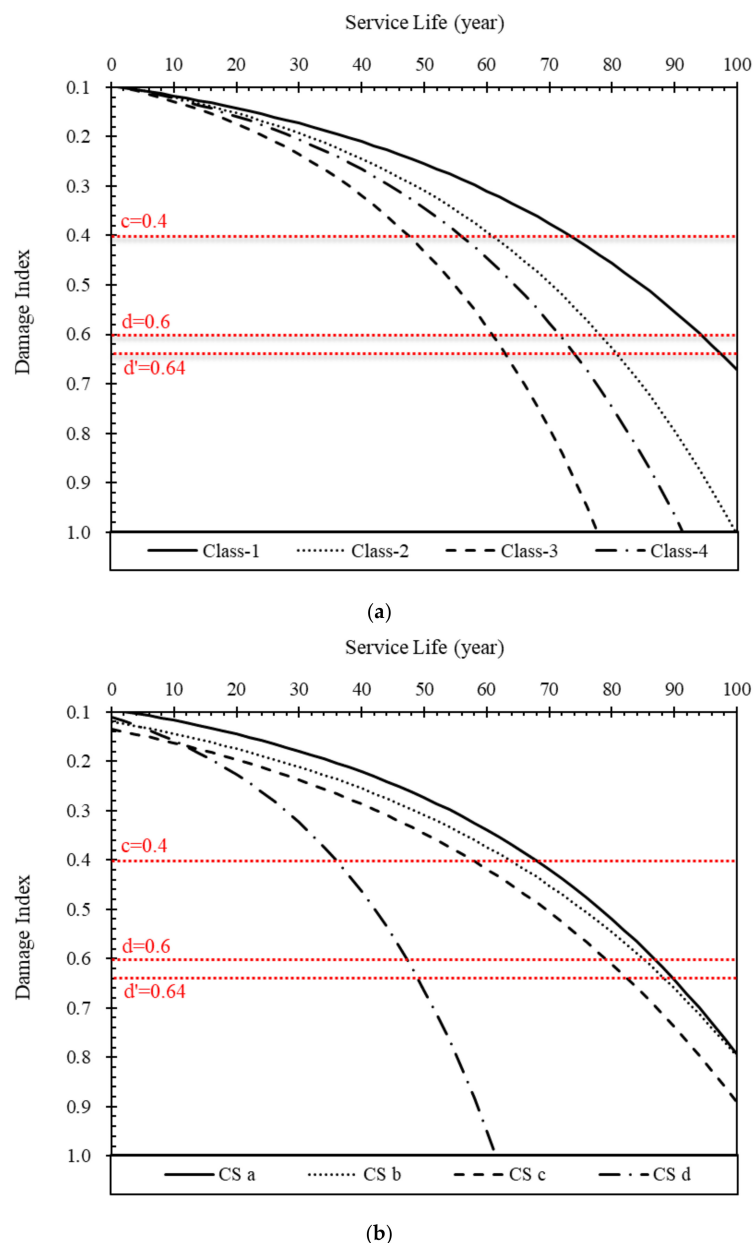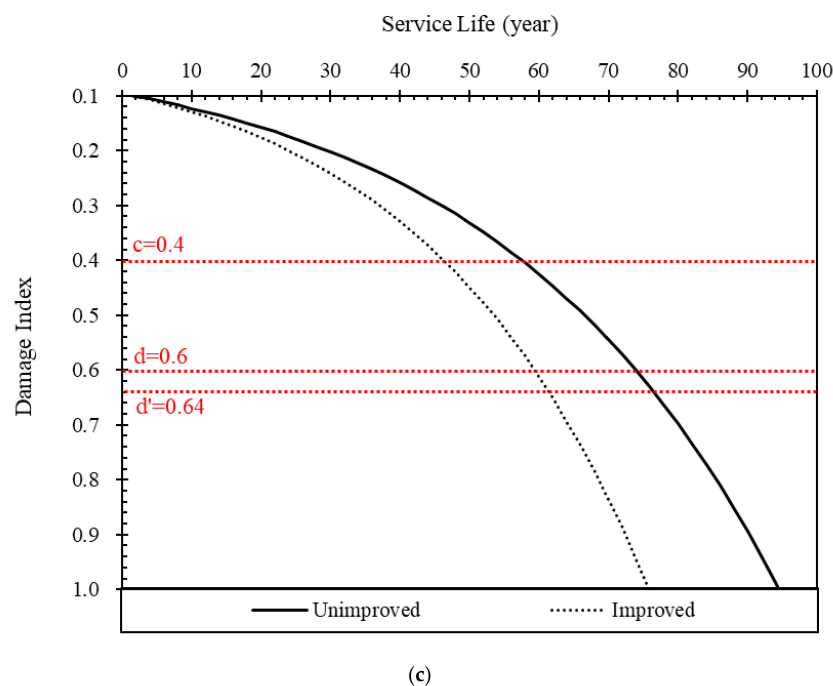

(a)

(b)

Figure 11. *Cont.*

(c)

Figure 11. Deck performance degradation curves for each deterioration factor. (**a**) Deicing agent exposure grade; (**b**) Pavement condition state; (**c**) Surface improvement status.

6. Prediction of the Residual Service Life of Bridge Decks

In this study, three types of condition grades were determined to predict the remaining life of bridge decks, and the period reaching that grade was determined as the remaining life; the grades are as follows:

- When repair is necessary due to minor deterioration or damage (grade c, DI = 0.4)
- When reinforcement is needed owing to the reduction in the load-carrying capacity of the bridge deck (graded, DI = 0.6)
- When a certain period of time has elapsed since the load carrying capacity has been reduced and reinforcement is needed (grade d', DI = 0.64) [35]

The remaining life of the bridge deck for each deterioration factor was derived as shown in Table 4, using the above-mentioned damage index and the reduced performance degradation curve of the bridge deck.

Table 4. Examination of the life of decks according to the deicing agent exposure grade.

Exposure Grade	Class-1	Class-2	Class-3	Class-4
c (DI = 0.4)	73	61	48	56
d (DI = 0.6)	94	78	61	72
d' (DI = 0.64)	97	81	63	74

In the case of the deicing agent exposure grade, the remaining life of decks decreased as the grade increased from Class-1 to Class-4 (Table 4). In addition, the time to reach the intermediate value of rating D, which is the end of life, was found to be 97 years for Class-1 with the smallest amount of deicing agents used and 74 years for Class-4 with the largest amount of deicing agents used, indicating that the life is reduced by 23 years. However, the results of this study revealed that the performance of Class-3 decks degraded faster than that of Class-4. This can be attributed to the fact that many bridges

with service lives between 5 and 15 years had low condition states, and because they were influenced by the synergistic effects of causes such as construction quality, route conditions, and deicing agents.

As the degradation of the pavement condition state causes damage to the pavement and waterproof layer, damage and deterioration in decks are accelerated as the condition state decreases. As the pavement condition state changed from a to d, the time to reach d', which is the end of life, decreased by 41 years from 90 to 49 years, as shown in Table 5; this confirms that the pavement condition state affects the performance degradation of decks. As there is likely a close correlation between the pavement damage condition and the performance degradation of decks, further research on this correlation is required.

Table 5. Examination of the life of decks according to the pavement condition state.

Pavement Condition State	a	b	c	d
c (DI = 0.4)	68	64	58	36
d (DI = 0.6)	87	85	79	47
d' (DI = 0.64)	90	88	82	49

In the case of the surface improvement status, the time to reach d' was found to be 61 years for the bridges improved once or more, which was 16 years faster than the unimproved bridges, as shown in Table 6. This appears to be because pavement repair or improvement performed after damage during service causes the deck to deteriorate, which leads to fast performance degradation. In the future, it will be necessary to solve this chronic problem by improving the quality of deck repair and improvement.

Table 6. Examination of the life of decks according to the surface improvement status.

Surface Improvement Status	Unimproved	Improved
c (DI = 0.4)	58	46
d (DI = 0.6)	74	59
d' (DI = 0.64)	77	61

One of the three remaining lives shown in Tables 4–6 was determined in order to suggest a process for prioritizing the maintenance of the bridge deck.

If the remaining life determination grade is c or d, it is possible to extend the service life of the bridge deck by quick repair and reinforcement, but considering the conditions of highways in Korea that have been in use for more than 50 years, excessive maintenance costs may be required. In consideration of this situation, the Korea Expressway Corporation determines and maintains the end of life of the bridge deck as the condition state d' [11]. Therefore, in this study, the remaining life of the bridge deck was determined as the condition state d and was used to derive the priority process for maintenance. The remaining life for each condition grade of the bridge deck derived based on the previously determined condition state d' (DI = 0.64) is shown in Table 7, and this table can be used to determine the priority of maintenance of the deck.

Table 7. Remaining life prediction results by deck condition state.

All	a→End	b→End	c→End	d→End
Class-1	97	60	24	3
Class-2	81	50	20	3
Class-3	63	38	15	2
Class-4	74	45	18	2
Pavement CS a	90	55	22	3
Pavement CS b	88	61	24	3
Pavement CS c	82	61	24	3
Pavement CS d	49	32	13	2
Unimproved	77	47	19	3
Improved	61	37	15	2

From the regression equations on Figure 10, an equation for determining of the remaining life (RL) of bridge decks proposed as follow by considering deterioration factors. By using Equation (1), the remaining life of bridge decks under certain deterioration condition and current age can be predicted easily.

$$RL = \frac{\ln(DI) - \ln(a)}{b} - CA \tag{1}$$

where,

RL = Remaining Life
DI = Targeting Damage Index (0.64)
CA = Current Age
a, *b* = Parameters depending on deterioration factors summarized in Table 8

Table 8. Parameters depending on deterioration factors.

Parameters	Deicing Agent Exposure Grade				Pavement Condition State				Improvement Status	
	Class-1	Class-2	Class-3	Class-4	CS a	CS b	CS c	CS d	Unimproved	Improved
a	0.0967	0.0951	0.0949	0.0948	0.0945	0.1195	0.1347	0.1107	0.0959	0.0947
b	0.0194	0.0236	0.0303	0.0258	0.0213	0.019	0.0189	0.0358	0.0248	0.0311

7. Determination of Maintenance Priorities

This study proposed a process for estimating the maintenance priority of decks, using the remaining life derived considering information on the highway bridge deck's condition state and deterioration factors, as shown in Figure 12. In this process, maintenance priority can be determined by identifying (1) the deck condition state, (2) deterioration factors for target bridges, (3) deriving the remaining life of the decks considering the deterioration factors, and (4) using the derived remaining life.
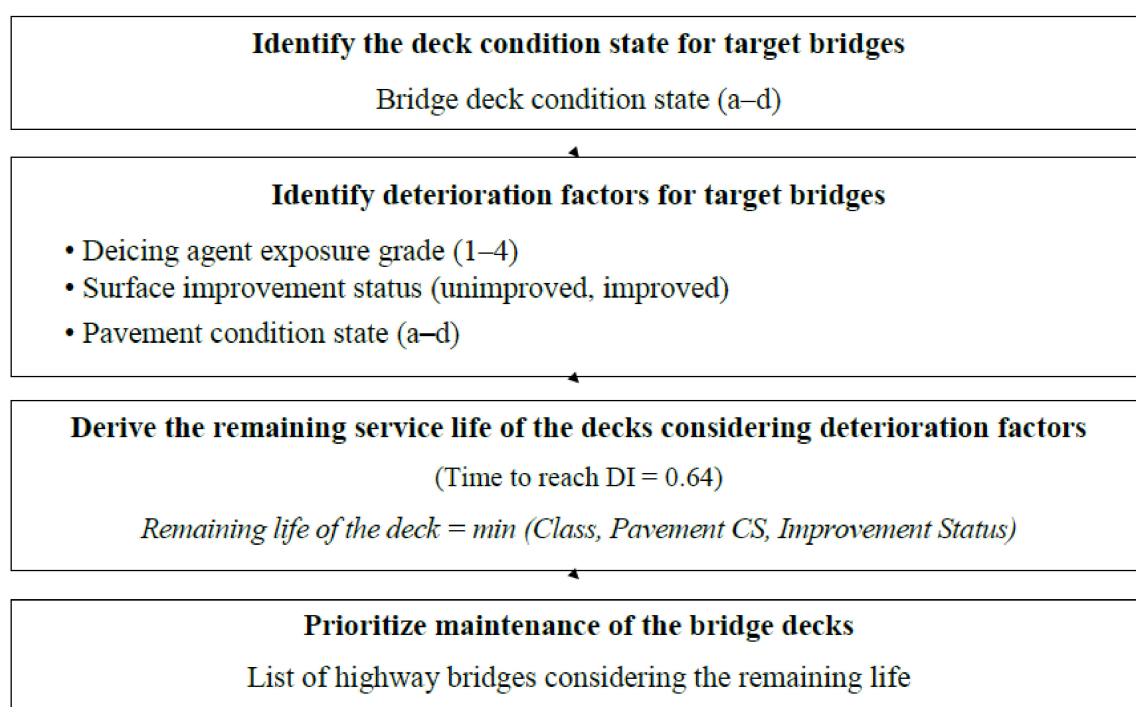
Identify the deck condition state for target bridges

Bridge deck condition state (a–d)

Identify deterioration factors for target bridges

- Deicing agent exposure grade (1–4)
- Surface improvement status (unimproved, improved)
- Pavement condition state (a–d)

Derive the remaining service life of the decks considering deterioration factors

(Time to reach DI = 0.64)

Remaining life of the deck = min (Class, Pavement CS, Improvement Status)

Prioritize maintenance of the bridge decks

List of highway bridges considering the remaining life

Figure 12. Process of prioritizing maintenance of highway bridge decks.

As an example of applying the estimation process for the deck maintenance priority derived above, one highway bridge (Sinyong Bridge) was selected as the target bridge, and its remaining life was derived as shown in Table 9. Its current deck condition was c, the exposure grade was Class-4, the pavement condition state was b, and there was no improvement. The remaining lives that considered the condition states c were 18, 24, and 19 years, and the minimum value of 18 years was determined to be the remaining life of the deck of the Sinyong Bridge. The reason for choosing the minimum value among the remaining life for each deterioration factor is to conservatively judge the end of life of the bridge deck.

Table 9. Highway bridge status data.

Basic Info.							Remaining Life According to Deterioration Factors from Table 7 (Year)			Final Remaining Life (Year)
Bridge Name	Completion Year	Service Period	Deck Condition State	Deicing Agent Exposure Grade	Pavement Condition State	Improvement Status	Deicing Agent Exposure Grade	Pavement Condition State	Improvement Status	
Sinyong Bridge	1973	37	c	Class-4	b	none	18	24	19	18

As shown above, the three deterioration factors are available in the HBMS database along with the deck condition states. Therefore, the remaining life of all highway bridges can be evaluated using the deck performance degradation curves and deterioration factors. Figure 13 shows the remaining life of 9443 highway bridges currently in service, obtained using the proposed process based on the maintenance database. The results showed that approximately 400 bridges will require replacement in 15 years, and more than 2000 bridges in 36–40 years. It appears that the replacement demand will sharply increase in 36–40 years, due to the rapid increase in construction quantity between 1990 and 2010.
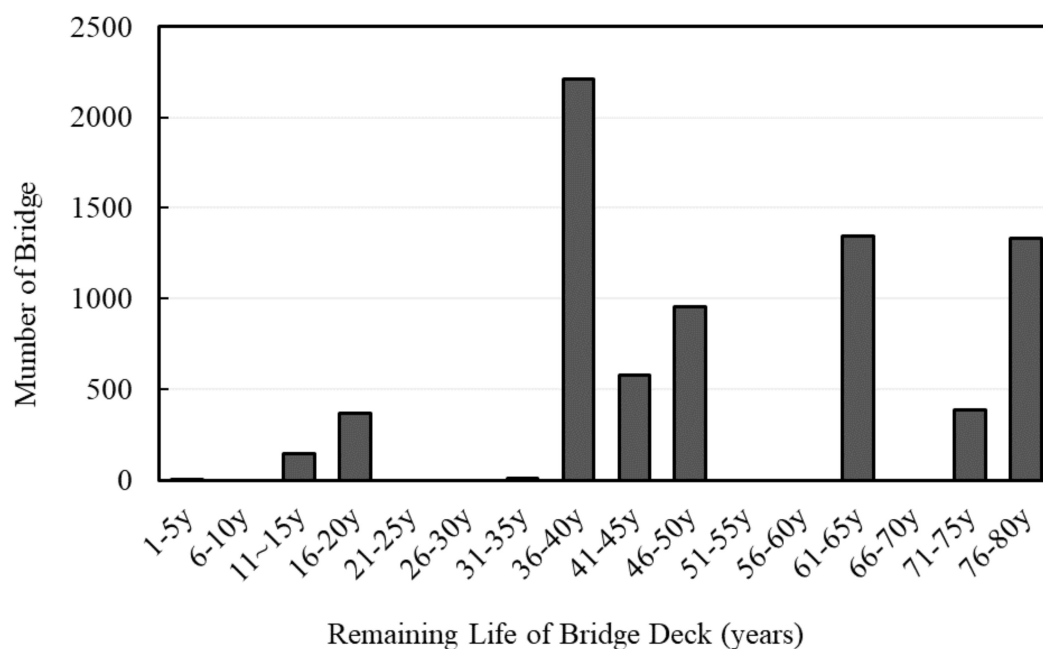
Figure 13. Replacement demand of highway bridges considering the remaining life.

The proposed process will enable planners to devise maintenance plans for routes, regions, and management branches, as well as maintenance budget execution plans, by preparing for the sharply increasing demand for deck replacement. In addition, by enabling preemptive and customized maintenance, considering the different deterioration environments for each bridge, the service life of decks is expected to increase.

8. Accomplishment of Bridges Decks Sustainability

The objective of the sustainability for bridges could be accomplished by ensuring durable bridges with a long service life and low maintenance inputs [36,37]. In order to accomplish a sustainability of bridge deck, the prioritization process for bridge deck maintenance developed in this study can be applied. As shown in Figure 14, a bridge deck with the shortest service life (curve A) can be served for 46 years and the rehabilitation or improvement of the deck should be conducted. Due to the improvement work of the deck, a lot of construction costs, environmental pollution such as noise and dust, and traffic jams may occur. If the prioritization process for bridge deck maintenance apply to this bridge deck and it is maintained at the right time, not only can the life of the bridge deck be extended, but also environmental pollution can be minimized. For example, if the life of a bridge deck is cut in half due to deterioration factors, it may require two instances of reconstruction work, compared to a bridge deck in good condition. In this case, the environmental pollution, such as the amount of construction waste, CO_2 emissions by producing cement and steel bar, dust generation, and air pollution due to traffic congestion, will be doubled per reconstruction.
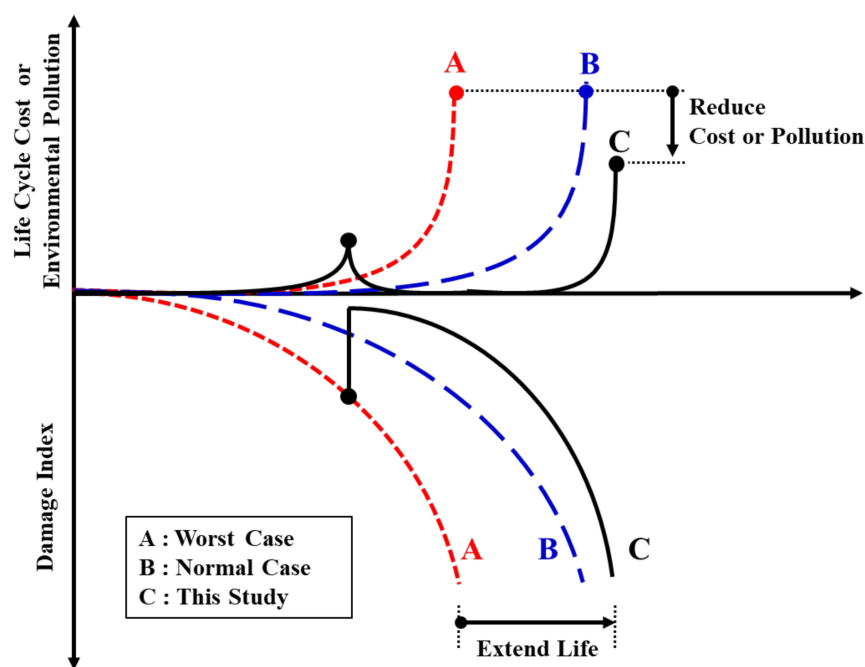
Figure 14. Example of accomplishment of bridge decks sustainability.

Furthermore, the current design of the bridge deck can be improved according to the remaining service life and deterioration factors proposed in this study. For example, a bridge deck design in the worst case of deicing agent exposure of Class-4, pavement condition state of d, and improved surface improvement condition should apply a reinforced design upon the existing design by applying epoxy coated rebar and high-strength concrete to protect from deterioration. Alternatively, under favorable deterioration conditions, it is possible to an optimize design by applying the existing design method. Therefore, by applying the results of this study, it is expected that the sustainability of the bridge deck can be accomplished with reduced life cycle costs while improving the current design.

9. Conclusions

This study proposed a method for bridge deck service life prediction, and applied it to determine maintenance priority to extend service life in an economical and sustainable fashion. The conclusions of this study, are as follows:

(1) Factors that can represent various deterioration factors for decks were examined; following three factors that can reflect combined deterioration and damage were selected and reflected in the analysis: (1) deicing agent exposure grade, (2) pavement condition state, and (3) surface improvement status.

(2) Performance degradation curves were derived for 11 cases that considered the representative three deterioration factors, and the performance degradation of decks was examined for each deterioration factor. The differences in the remaining life according to the deicing agent exposure grade between Class 1 and 4, the pavement condition state between CS a and d, and the absence or existence of the bridge surface improvement status were 23, 41, and 16 years, respectively.

(3) A new method for predicting the remaining life of bridge decks was proposed by considering certain deterioration conditions and the current age, based on more than 120,000 points of actual field data.

(4) A process to determine maintenance priorities using the current condition of highway bridges and the deterioration factors of individual bridges was proposed. The maintenance demand was predicted based on the end of deck life. The results indicated that the demand for deck

replacement will sharply increase in 15 years, and that the decks of more than 2000 bridges will reach the end of their service lives in 40 years.

(5) Structural characteristics of the decks make it challenging to perform maintenance at the proper time, thus preventing their efficient maintenance. The proposed process of prioritizing deck maintenance makes it possible to predict the demand for deck repair and reinforcement. By enabling maintenance personnel to derive maintenance priorities through the classification of various factors by route, region, and pavement type, the proposed process is expected to help increase the service life of decks and reduce maintenance costs.

(6) By applying the prioritization process for bridge deck maintenance to the bridge deck, not only can the life of the bridge deck be extended, but also environmental pollution can be minimized. Additionally, an optimizing design for bridge decks by considering remaining life and deterioration factors can be possible. Therefore, this study expects that the sustainability of bridge decks can be accomplished.

(7) In this study, an analysis was performed to extend the life of the deck, one structure member of the entire bridge. If this analysis method is applied to other structure members such as super-structure and sub-structure, the life of the entire bridge can also be extended. By securing the sustainability of the bridge, as well as the bridge deck, it will be possible to maximize the reduction in maintenance costs and environmental pollution.

(8) Highway bridges in Korea were actively built in the 1990s and 2000s. As bridges built during this period have now aged for more than 30 years, safety accidents such as collapse are of concern. Improving these aging infrastructures in a sustainable manner can help to secure the safety of infrastructure users and improve the quality of life of the community.

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