Data-Driven Life-Cycle Cost Analysis of Corrosion-Affected Elastomeric Bridge Bearing Assemblies Using Survival Models and Monte Carlo Simulation

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Abstract

Elastomeric bridge bearing assemblies are critical structural components that facilitate load transfer and accommodate movements in bridge systems; however, their long-term performance can be susceptible to corrosion-induced deterioration, particularly in aggressive environments. Despite their widespread use, the economic implications of such degradation remain insufficiently quantified using data-driven and probabilistic approaches. This study presents a data-driven life-cycle cost analysis (LCCA) method that integrates survival analysis with probabilistic cost modelling to evaluate the long-term economic performance of corrosion-affected elastomeric bridge bearing assemblies. Inspection and element-level condition rating data from the FHWA National Bridge Inventory database are used to characterize deterioration behaviour. A nonparametric Kaplan-Meier estimator is first applied, followed by parametric survival modelling using candidate distributions including Weibull, lognormal, log-logistic, and hypertabastic models. The best-fit model, selected based on statistical criteria, is integrated into a Monte Carlo based LCCA to capture uncertainties in replacement timing, cost variability, and economic discounting. Results show that corrosion-driven replacement behaviour dominates long-term cost outcomes, with substantial variability across plausible scenarios. Sensitivity analyses indicate that discount rate assumptions and service-life uncertainty are the primary drivers of cost variability. The proposed framework provides a data-driven and risk-informed basis for bridge asset management and maintenance planning.

Keywords: Elastomeric bridge bearings; Life-cycle cost analysis (LCCA); Survival analysis; Corrosion deterioration; Probabilistic modelling

1. Introduction

Bridge bearings are critical structural components that transfer loads from the superstructure to the substructure while accommodating rotations, translations, and thermal movements induced by traffic loads and environmental effects (AASHTO, 2020; Lee, 1994; Mohan & Krishnankutty, 2017). Without properly functioning bearings, restraint forces may accumulate within bridge components, leading to cracking, overstressing, or even premature structural deterioration (FHWA, 2023). Historically, mechanical systems such as sliding, rocker, roller, and pin bearings were widely used; however, these steel-on-steel mechanisms are susceptible to wear and corrosion and often require intensive maintenance. Modern practice increasingly favours elastomeric, pot, disc, and spherical bearings, which combine steel and polymeric materials to improve durability, reduce maintenance demands, and enhance seismic and vibration performance (Fasheyi, 2012).

Elastomeric bearings consist primarily of layers of rubber (typically neoprene or natural rubber) reinforced with steel laminates to provide vertical stiffness while allowing horizontal flexibility and rotational capacity (Mohan & Krishnankutty, 2017). Since their widespread adoption beginning in the mid-20th century, elastomeric bearings have largely replaced older steel rocker and roller bearings in new bridge construction and rehabilitation projects (Wetzk, 2006; English, 1993; Sengsri & Kaewunruen, 2020). Analysis of annual element-level data from the U.S. Federal Highway Administration (FHWA) National Bridge Inventory (NBI) (FHWA, n.d.-a; FHWA, n.d.-b) indicates a clear shift in bearing usage within Maryland bridges between 2016 and 2025, with elastomeric bearings showing a consistent increase and emerging as the dominant bearing type (Fig. 1). In contrast, the proportion of traditional mechanical bearings has remained stable or declined. This transition reflects the advantages of elastomeric bearings, including structural simplicity, lower fabrication and maintenance costs, and inherent damping characteristics that mitigate traffic- and wind-induced vibrations (Roeder & Stanton, 1983; Research and Markets, n.d.).

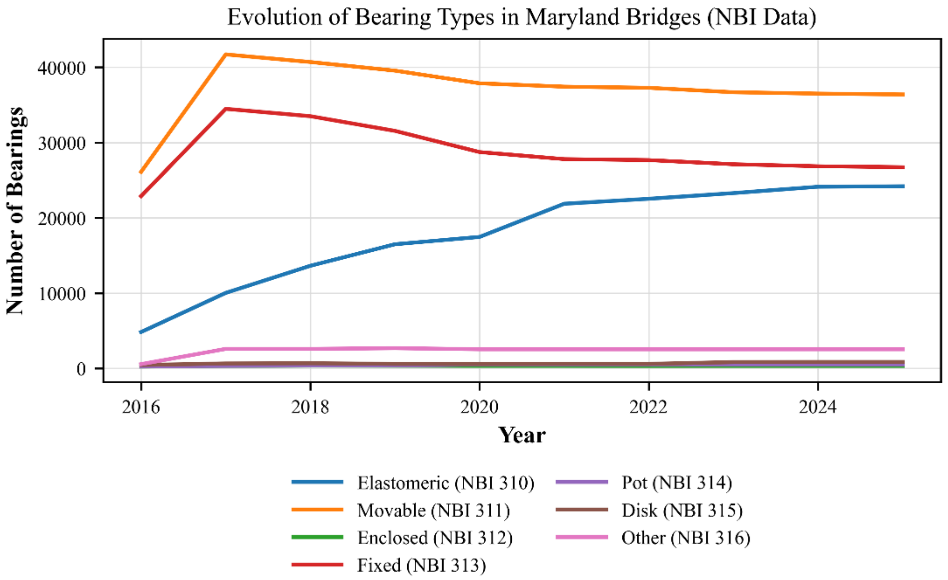


Figure 1. Temporal distribution of bridge bearing types in Maryland based on National Bridge Inventory (NBI) element-level data (2016-2025). Elastomeric bearings (NBI 310) show a consistent increase over time, reflecting their growing adoption, while traditional movable and fixed bearings exhibit declining trends.

Despite their advantages, elastomeric bearing assemblies are vulnerable to corrosion-related deterioration, particularly in aggressive service environments. Corrosion is one of the most dominant deterioration mechanisms affecting steel bridge components (Bao et al., 2021), and deicing chemicals, especially chloride-based salts, are widely recognized as major contributors to corrosion in cold-region transportation infrastructure (Azizinamini et al., 2014). Coastal exposure and chemically aggressive environments further accelerate corrosion processes. Bearings located beneath leaking deck joints or exposed to roadway drainage are especially susceptible to deterioration due to continuous exposure to moisture, deicing salts, and cyclic thermal variations. These conditions promote corrosion of internal steel reinforcement plates, external bearing plates, anchor assemblies, and adjacent structural steel components. In addition, accumulated debris and inadequate drainage can further exacerbate moisture retention, creating localized corrosive micro-environments that further accelerate deterioration (Kogler, 2012). Field observations conducted in this study (Fig. 2) reveal significant corrosion-induced damage in elastomeric bearing assemblies, including steel section loss, rust accumulation, and degradation of bearing components, which will lead to premature replacement relative to their nominal design life. From an asset management perspective, such corrosion-driven deterioration presents not only a structural concern but also a significant economic challenge. Bearing replacement operations are typically labour-intensive and costly, requiring superstructure jacking, traffic control, and specialized access equipment. Consequently, even moderate reductions in bearing service life can substantially increase long-term life-cycle costs. In this study, elastomeric bearings refer to laminated elastomer-steel bearing units, including internal steel shims, bonded external steel plates, anchor bolts, and the associated bearing assembly.

Figure 2. Field observations of corrosion-induced deterioration in elastomeric bridge bearing assembly with condition rating 3, showing severe rusting, section loss, and delamination of steel components due to prolonged exposure to moisture, water leakage, low clearance above water, and coastal and deicing salts.

Life-cycle cost analysis (LCCA) provides a systematic framework for evaluating the total economic performance of infrastructure components over a defined analysis horizon, incorporating initial construction costs, maintenance expenditures, rehabilitation actions, replacement costs, and discounting effects (Frangopol & Liu, 2007; Gu, Chang, & Liu, 2009; Walls & Smith, 1998). The fundamental objective of LCCA is to identify the most cost-effective alternative by accounting for all relevant long-term expenditures rather than relying solely on initial cost comparisons (Flanagan & Jewell, 2005). In the context of bridge bearings, LCCA enables infrastructure owners and transportation agencies to quantify long-term economic impacts in regions where bearings are exposed to aggressive environments and corrosion, and to evaluate potential alternatives such as stainless-steel bearing systems based on lifetime economic performance. In transportation infrastructure, LCCA has been widely applied to pavement systems, bridge decks, and rehabilitation strategies to support investment decision-making at both project and network levels (Walls & Smith, 1998; FHWA, 2002).

Several studies have advanced LCCA methodologies for bridge systems. Ozbay, Jawad, Parker, & Hussain (2004) reviewed the evolution of LCCA practices among U.S. State Highway Agencies and highlighted variations in implementation approaches. Ehlen (1999) emphasized the importance of incorporating agency, user, and third-party costs in bridge evaluations. Eamon, Jensen, Grace, & Shi (2012) performed LCCA for prestressed concrete bridges under varying traffic conditions, while Zhang, Novick, Hadavi, & Krizek (2005) examined life-cycle cost (LCC) considerations for bridges and tunnels including major rehabilitation and annual maintenance. Leiva Maldonado & Bowman (2019) applied LCCA to short- and medium-span bridges considering different superstructure alternatives. Material-specific life-cycle investigations have further demonstrated the economic implications of corrosion resistance. Okasha, Frangopol, Fletcher, & Wilson (2012) compared conventional painted steel girders with stainless steel alternatives, and Soliman & Frangopol (2014) conducted a probabilistic life-cycle assessment including indirect user costs, concluding that corrosion-resistant steel may offer superior long-term sustainability in aggressive environments. These studies collectively demonstrate the importance of integrating durability considerations within economic evaluations. Despite substantial progress in bridge-level LCCA research, no published studies explicitly integrate corrosion-driven probabilistic service-life modelling with LCCA of elastomeric bridge bearings based on large-scale inspection data.

Maryland provides a particularly relevant case study due to its coastal exposure, freeze-thaw cycles, and extensive use of deicing salts, all of which accelerate corrosion in bridge components. In addition, consistent element-level reporting within the FHWA NBI enables data-driven characterization of elastomeric bearing deterioration using a survival analysis framework. Building on this dataset, this study integrates survival analysis with probabilistic life-cycle cost modelling to quantify the economic implications of corrosion-driven deterioration in elastomeric bridge bearings. First, multiple parametric survival models, including Weibull, log-logistic, and hypertabastic distributions, are evaluated to estimate time-to-replacement using large-scale NBI inspection data. Second, the selected survival model is embedded within a Monte Carlo-based LCCA framework to capture uncertainty in replacement timing, cost variability, and economic discounting. Third, sensitivity analyses are conducted to examine the influence of key parameters, including discount rate, replacement cost, and service-life variability, on long-term cost outcomes. The results demonstrate that the Weibull model provides the most robust representation of corrosion-driven bearing deterioration and that replacement timing and discount rate are the dominant drivers of life-cycle cost variability, whereas uncertainty in routine maintenance costs has a comparatively minor impact. These findings establish a probabilistic foundation for evaluating bridge bearing management strategies and provide a framework for comparing conventional elastomeric bearing design with corrosion-resistant alternatives.

2. Data and Methods

2.1. Data Source and Case Study

This study utilizes inspection and element-level condition data obtained from the U.S. FHWA NBI database, which provides standardized inventory, inspection, and condition information for public highway bridges in the United States reported under the National Bridge Inspection Standards (NBIS) (FHWA, n.d.-b; FHWA, n.d.-c). In addition to conventional bridge inventory records, the NBI includes element-level datasets that report quantities of individual bridge elements categorized by condition state, submitted annually by state and federal agencies as part of the inspection and reporting process (FHWA, n.d.-b).

The analysis focuses on conventional elastomeric bridge bearings, represented in the NBI element framework by Elastomeric Bearings (Element No. 310), where quantities are reported on a per-bearing basis (unit: each) (FHWA, 2022a). For each bridge, the NBI element data report the total quantity of elastomeric bearings and their distribution across four condition states (CS1 - CS4), which represent increasing levels of deterioration from good to severe (FHWA, n.d.-b; FHWA, 2014). Condition State 1 (CS1) represents bearings in good condition, while CS2 and CS3 indicate increasing levels of deterioration. Condition State 4 (CS4) corresponds to severe deterioration and reflects conditions associated with loss of serviceability or structural capacity requiring engineering evaluation (FHWA, 2014; FHWA, 2023; NJDOT, 2015).

The case study considers bridges located in the State of Maryland (MD, USA). NBI records were filtered to include only Maryland-reported public highway bridges with available inspection histories and corresponding element-level bearing data. The analysis utilizes annual NBI datasets spanning 2015 - 2025, a period that provides consistent coverage of element-level inspection data following nationwide implementation of element-based reporting. To support deterioration and survival analysis, element-level bearing data were integrated with bridge inventory records using bridge structure numbers as a common identifier. Since bearing installation dates are not explicitly reported in the NBI element dataset, bridge age derived from inventory records was used as a proxy for bearing age. However, because bridge age may not accurately represent the true age of individual bearings due to potential replacement interventions, bearings with estimated ages greater than 50 years were excluded, consistent with the typical service life range of elastomeric bearings (40 - 50 years) (Kulicki, Wassef, Nowak, Mertz, & Samtani, 2015; FHWA, 2022b). The combined dataset was processed to remove duplicate entries and ensure consistency across inspection years.

Corrosion-affected elastomeric bearings were identified based on condition state information and associated steel protective coating condition ratings. In this study, bearings exhibiting advanced deterioration (CS $\geq$ 3) in conjunction with corrosion-related indicators were considered functionally failed components requiring replacement. Accordingly, only bearings classified in condition states CS3 and CS4 were retained for analysis. Since condition state ratings are assigned at discrete inspection intervals, a bearing recorded as CS3 may have already progressed toward more severe deterioration between inspections. Therefore, CS3 is treated as the onset of functional failure, while CS4 represents an advanced stage of deterioration. The spatial distribution of bridges with corrosion-affected bearings in Maryland is shown in Fig. 3. Bridge locations are derived from NBI records and plotted using geographic coordinates. As shown in the figure, affected bridges are more concentrated in coastal regions and along major transportation corridors where exposure to moisture, marine aerosols, and deicing salts is prevalent. These environmental conditions contribute to accelerated corrosion of bearing components, including steel plates and anchorage systems, supporting the role of environmental exposure in bearing deterioration. Summary statistics derived from the processed dataset are used to characterize deterioration trends and support the probabilistic LCCA presented in subsequent sections.

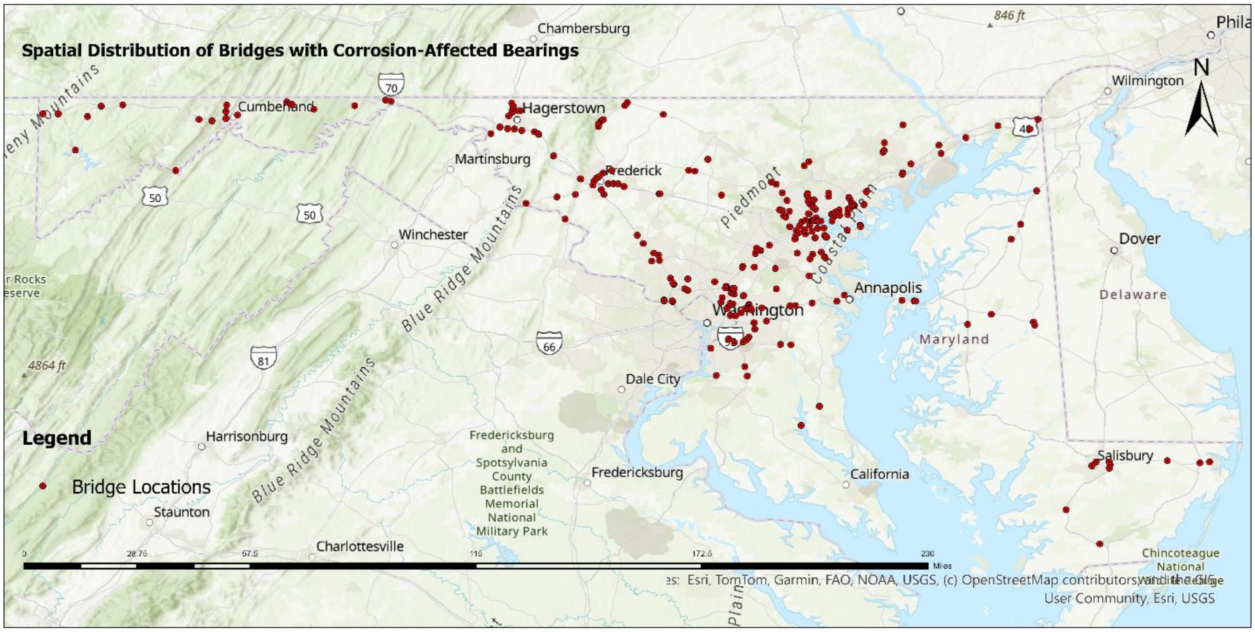


Figure 3. Spatial distribution of bridges with corrosion-affected bearings in Maryland.

2.2. Life-Cycle Cost Analysis Approach for Bridge Bearings

Traditional LCCA applications often rely on deterministic service-life assumptions and single-point cost estimates. Such approaches may underestimate economic risk, particularly when deterioration processes exhibit substantial variability. Probabilistic LCCA frameworks incorporating stochastic deterioration models and Monte Carlo simulation have been recommended for infrastructure systems subject to uncertainty (Cadenazzi, Lee, Suraneni, Nolan, & Nanni, 2021; Han, Lee, and Park, 2022; Sánchez-Silva & Klutke, 2016; Shahid et al., 2025). Yet, published applications of probabilistic LCCA specifically addressing elastomeric bridge bearings and corrosion-induced replacement timing remain scarce.

Survival analysis comprises a class of data-driven statistical techniques used to analyse time-to-event processes and estimate the probability of failure over time. Originally developed and widely applied in biomedical and epidemiological research to study patient survival and disease progression, these methods have increasingly been adopted in engineering reliability analysis and infrastructure deterioration modelling (Tabatabai, Bursac, Williams, & Singh, 2007). These approaches provide a statistically rigorous framework for estimating time-to-failure distributions when datasets include censored observations, which commonly occur in infrastructure inspection records. Among the survival analysis methods, the Kaplan-Meier estimator enables non-parametric estimation of survival probabilities without imposing distributional assumptions (Goel, Khanna, & Kishore, 2010; Goyal, Whelan, & Cavalline, 2019; Kaplan & Meier, 1958), while parametric survival models, such as the Weibull, log-logistic, and hypertabastic distributions, allow characterization of deterioration processes and aging mechanisms frequently observed in structural components (Elmahdy, 2015; Li, Fu, & Guo, 2025). These methods have been increasingly adopted in infrastructure asset management for modelling deterioration of pavements, bridge decks, and structural elements (Beng & Matsumoto, 2012; Fleischhacker, Ghonima, & Schumacher, 2020; Hatoum, Khatib, Barraj, & Elkordi, 2022; Jiang, Saito, & Sinha, 1988; Li, Lu, & Peng, 2022; Nabizadeh, Tabatabai, & Tabatabai, 2019; Tabatabai, Lee, & Tabatabai, 2014; Tabatabai, Lee, & Tabatabai, 2015). The availability of element-level condition data within the FHWA NBI offers a valuable opportunity to apply survival analysis to bridge bearing deterioration at a statewide scale.

The LCCA framework adopted in this study evaluates the total economic cost of elastomeric bridge bearings over the design service life of a bridge by accounting for all relevant costs incurred from initial construction through inspection, maintenance, and replacement. The total LCC is expressed as

$$\mathrm{LCC} = \mathrm{ISC} + \mathrm{IIC} + \mathrm{IMC} + \mathrm{DRC} + \mathrm{UC} \tag{1}$$

where ISC is the initial supply cost of the bearing assembly, IIC is the initial installation cost at the time of bridge construction, IMC represents inspection and routine maintenance costs incurred during service, DRC is the direct replacement cost associated with bearing replacement events, and UC denotes user costs associated with traffic disruption during maintenance or replacement activities. This formulation follows standard practice in infrastructure LCCA, where both agency and user costs are considered where applicable (FHWA, 2002). In the present study, the analysis is conducted from the perspective of the owning agency; therefore, user costs (UC) are assumed to be zero. This assumption reflects the lack of reliable bearing-specific traffic disruption data and the common practice of coordinating bearing replacement with other maintenance activities, thereby minimizing additional user impacts.

Initial supply and installation costs (ISC and IIC) are assumed to occur at year zero and represent the baseline investment associated with bearing provision during bridge construction. Inspection and maintenance costs (IMC) are modelled as recurring expenditures incurred at regular intervals throughout the service life, reflecting routine inspection, cleaning, and minor maintenance activities typical of bridge management programs. Direct replacement costs (DRC) are incurred when corrosion-driven deterioration reaches a condition requiring bearing replacement, as determined through the survival analysis framework described in subsequent sections. To capture uncertainties associated with both deterioration processes and cost estimation, the LCCA framework is implemented probabilistically using Monte Carlo simulation. Cost components and replacement times are treated as random variables characterized by prescribed probability distributions, enabling the generation of probabilistic LCC trajectories and risk-based metrics such as mean, median, and percentile values. The adopted probabilistic modelling approach and associated distributional assumptions are detailed in subsequent sections.

For a representative elastomeric bearing assembly typical of short- to medium-span bridges in Maryland, cost components were estimated based on engineering calculations and cross-validated using state DOT data and practitioner input. The material cost of the bearing assembly, including sole and masonry plates, elastomeric pads, internal steel laminates, and anchorage components, is estimated at approximately $1,220 per bearing. Fabrication of the complete bearing assembly, including steel plates and manufacturing processes, is estimated at $1,000 per bearing, while initial installation at the construction stage is estimated at $1,500 per bearing. These values result in a combined initial cost (ISC + IIC) of approximately $3,720 per bearing, which is consistent with reported ranges from DOT data and engineering practice (typically $3,000 - $5,000 per bearing) (National Academies of Sciences, Engineering, and Medicine [NASEM], 2020; Ohio Turnpike and Infrastructure Commission [OTIC], 2025; Texas Department of Transportation [TxDOT], 2023). Inspection and maintenance are essential components of effective bridge management, particularly for bridge bearings, which are subjected to significant stresses and environmental exposure. In this study, each bearing is assumed to undergo inspection every two years, requiring approximately 0.5 hours per inspection, along with minor maintenance activities such as cleaning. Using an average labour rate of $80 per hour, this results in an IMC of $40 per bearing every two years. A CV of 0.20 is adopted for ISC, IIC, and IMC, representing moderate uncertainty consistent with commonly reported ranges in infrastructure cost modelling. Sensitivity analyses are performed to evaluate the influence of alternative CV assumptions on LCC outcomes. The cost components and associated probabilistic assumptions used in the LCCA framework are summarized in Table 1.

The cost of elastomeric bearing replacement is governed primarily by construction-related operations rather than the bearing component itself. While the material cost of a new bearing assembly typically represents less than 10% of the total replacement cost, the majority of expenditures arise from superstructure jacking, temporary support systems, traffic control, and labour-intensive installation procedures. Accordingly, the DRC is decomposed into supply, installation, and preliminary engineering components. The supply cost is assumed to be consistent with the initial fabrication cost (approximately \$2,220 per bearing). The installation component includes activities such as lifting the superstructure using hydraulic jacks, temporary shoring and load transfer operations, removal of existing bearings, placement and alignment of new bearings, grouting and skilled labour crews. Preliminary engineering costs include design, planning, scheduling, cost estimation, and project management activities. For short- to medium-span bridges, replacement costs are highly variable and strongly dependent on site-specific conditions such as accessibility, traffic control requirements, and construction staging complexity. Evidence from state DOT bid tabulations indicates that while direct bearing costs are relatively low, associated construction operations contribute substantially to total replacement costs, which commonly reach the order of tens of thousands of dollars per bearing. Based on representative DOT data and engineering judgment (TxDOT, 2023), installation and preliminary engineering costs are collectively estimated at approximately \$25,000 per bearing in this study. Replacement cost variability is modelled using a lognormal distribution with a coefficient of variation (CV) of 0.359, reflecting the strong dependence of replacement costs on bridge-specific factors such as span length, number of bearings, access constraints, and construction staging requirements. Additional sensitivity analyses are conducted to evaluate the influence of alternative variability assumptions on LCC results.

Table 1. Breakdown of cost components and uncertainty parameters for elastomeric bearing life-cycle cost analysis.

Cost Component	Subcomponent	Symbol	Mean Value (USD per bearing)	Distribution	CV	Notes
Initial Supply Cost (ISC)	Material (sole and masonry plates + elastomer + steel laminates + anchors)	ISC_1	1,220	Lognormal	0.20	Based on engineering estimate and DOT data
	Fabrication (bearing assembly + steel plates)	ISC_2	1,000	Lognormal	0.20	Includes manufacturing and shop fabrication
Initial Installation Cost (IIC)	Installation at construction stage	IIC	1,500	Lognormal	0.20	Includes placement, alignment, and grouting
Total Initial Cost	ISC + IIC	ISC + IIC	3,720	Lognormal	0.20	Consistent with DOT-reported range ($3k-$5k)
Inspection & Maintenance Cost (IMC)	Routine inspection + minor maintenance (every 2 years)	IMC	40 (per 2 yrs)	Lognormal	0.20	Assumes 0.5 hr at $80/hr
Direct Replacement Cost (DRC)	Supply (replacement bearing assembly)	DRC_1	2,220	Lognormal	0.359	Same as initial fabrication + material
	Installation + preliminary engineering	DRC_2	25,000	Lognormal	0.359	Includes jacking, traffic control, labour, design
User Cost (UC)	–	UC	0	–	–	Neglected (agency perspective)

2.3. Cost Modelling and Uncertainty

Cost estimates associated with bridge bearings are subject to significant uncertainty due to variability in project characteristics, construction practices, site conditions, and inspection and maintenance strategies. To reflect this uncertainty and avoid deterministic LCC estimates, all cost components in the LCCA framework are modelled probabilistically and evaluated using Monte Carlo simulation. Baseline mean values for ISC, IIC, IMC, and DRC are specified in constant base-year U.S. dollars and represent typical agency-level estimates for elastomeric bridge bearing assemblies.

Inspection and maintenance costs are modelled as recurring expenditures incurred at regular two-year intervals over the analysis horizon, reflecting standard bridge inspection and minor maintenance practices under the NBIS. Replacement costs are incurred only when corrosion-driven deterioration triggers a bearing replacement event, as determined probabilistically through the survival modelling described. Different levels of uncertainty are assigned to individual cost components. Initial supply, installation, and inspection/maintenance costs are modelled using a lognormal probability distribution, which is appropriate for cost variables because it preserves non-negativity and captures the right-skewed characteristics typically observed in infrastructure cost data (Limpert, Stahel, & Abbt, 2001; Smart, 2017). A coefficient of variation (CV) of 0.20 is adopted for these cost components, representing a moderate level of uncertainty. A sensitivity analysis is subsequently performed to evaluate the impact of alternative CV assumptions on the LCC results.

The selection of the CV for replacement costs is informed by an exploratory analysis of span length distributions for short- to medium-span bridges with elastomeric bearings in Maryland. The span-length dataset was evaluated using several candidate probability distributions, including normal, lognormal, gamma, and Weibull distributions. Model selection based on the Akaike Information Criterion (AIC) (Akaike, 1974) indicated that the lognormal distribution provided the best representation of the observed span-length data (AIC = 2637), outperforming gamma (AIC = 2648), Weibull (AIC = 2678), and normal distributions (AIC = 2728). Based on this analysis, the lognormal distribution with a calculated coefficient of variation of 0.359 was adopted to represent replacement cost variability in the Monte Carlo simulation. This variability reflects the stronger sensitivity of replacement costs to bridge-specific factors such as span length, bearing quantity, access constraints, and construction staging requirements. Fig. 4 illustrates the span length distribution of short to medium span Maryland bridges with elastomeric bearings and the fitted lognormal distribution. Because replacement costs scale strongly with span length and associated construction complexity, the observed span-length variability is considered a reasonable proxy for uncertainty in bearing replacement costs. In the Results and Discussion section, sensitivity analyses are performed to assess the influence of these assumptions on LCC outcomes.

The LCCA in this study is limited to conventional elastomeric bearing assemblies representative of short- to medium-span bridges. A representative elastomeric bearing configuration is adopted, and the probabilistic analysis is performed based on this unit to ensure consistency across cost and deterioration modelling.

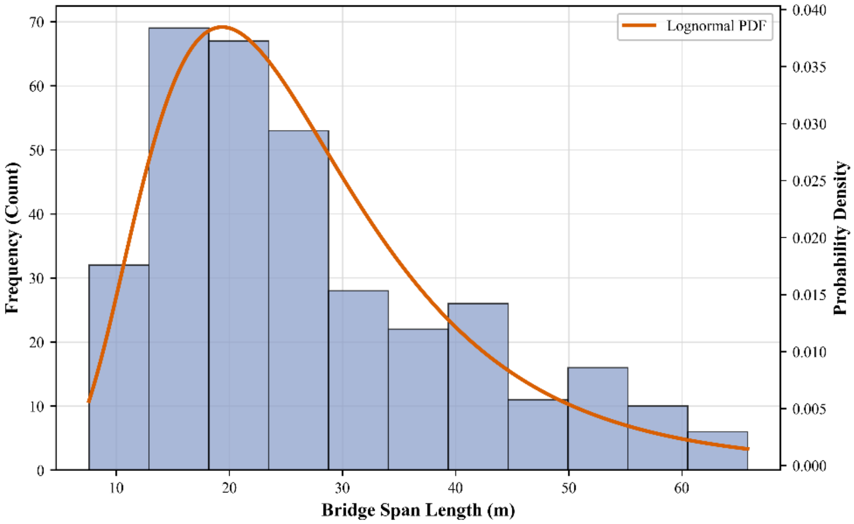


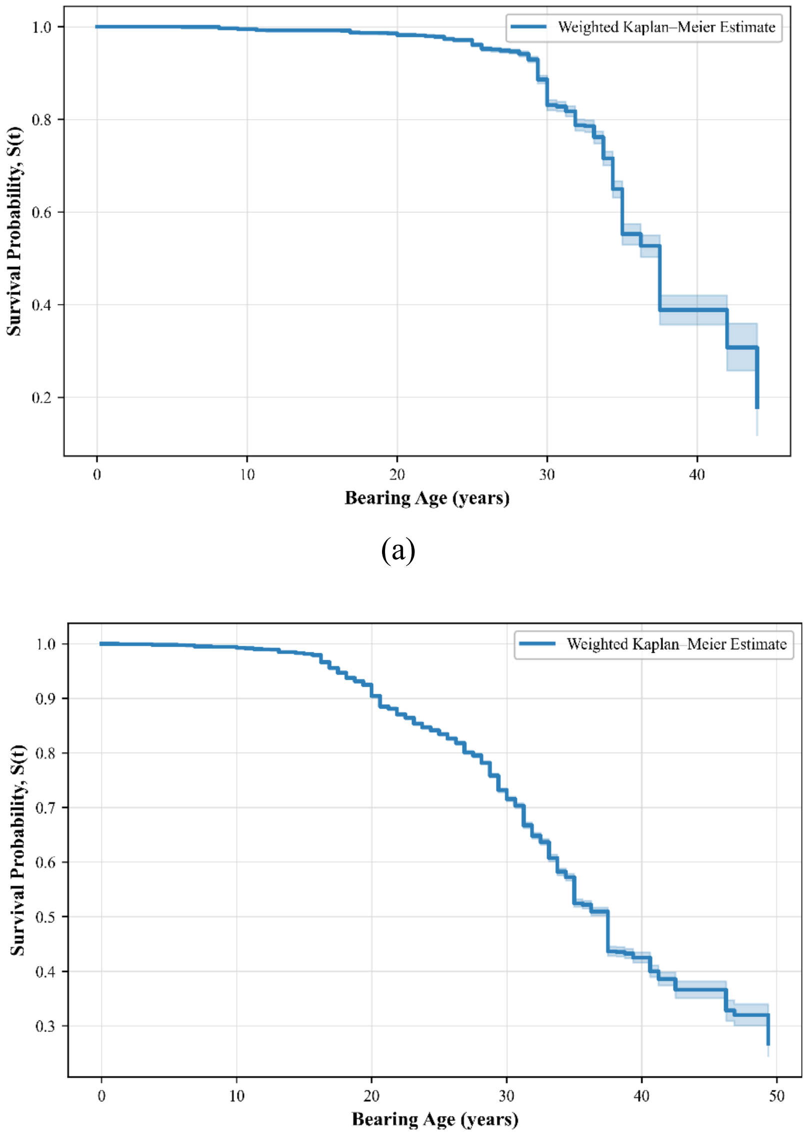
Figure 4. Histogram of span lengths for Maryland bridges (short- to medium-span) with elastomeric bearings together with the fitted lognormal probability density function. The lognormal distribution was selected as the best-fitting model based on Akaike Information Criterion (AIC) comparison with normal, gamma, and Weibull distributions.

2.4. Replacement Time Modelling

The timing of bearing replacement is governed by corrosion-driven deterioration and is modelled probabilistically using survival analysis techniques applied to historical inspection data. Bearing condition state histories extracted from the NBI for the period 2015-2025 for bridges in Maryland, USA are used to characterize the progression of elastomeric bridge bearings toward severe deterioration states indicative of functional failure. Corrosion-affected elastomeric bearings were identified based on condition state information and associated steel protective coating condition ratings. In this study, bearings exhibiting advanced deterioration (CS $\geq$ 3) in conjunction with corrosion-related indicators were considered to have reached a condition requiring replacement, and only these bearings were retained for analysis.

2.5. Kaplan-Meier Nonparametric Survival Analysis

A nonparametric Kaplan-Meier estimator was first employed to estimate the empirical survival function of elastomeric bridge bearing assemblies. The Kaplan-Meier method is well suited for infrastructure deterioration studies because it accommodates right-censored data, which arise when bearings have not yet reached failure by the end of the observation period. Figure 5 presents the Kaplan–Meier survival curves for (a) elastomeric bearing assemblies only and (b) all bearing types included in the dataset, corresponding to 258 and 2981 bridges, respectively. The shaded regions represent the associated confidence intervals. The survival curve for elastomeric bearing assemblies in Fig. 5a indicates a prolonged early-life period with minimal corrosion-related deterioration, with survival probabilities remaining close to unity for approximately the first 30 years. Beyond this period, the curve exhibits a steeper decline, suggesting an accelerated wear-out phase associated with increasing corrosion-related damage. Similarly, the survival curve for the complete bearing dataset in Fig. 5b shows limited early-life deterioration, followed by a progressive reduction in survival probability as bearing age increases. A more pronounced decline is observed after approximately 20 years, indicating the onset and propagation of corrosion-driven deterioration mechanisms. In both analyses, the widening confidence intervals at later ages reflect increased statistical uncertainty due to the decreasing number of bearings remaining at risk. The Kaplan-Meier analysis yielded mean corrosion-driven service lives of 37.05 years for elastomeric bearing assemblies and 36.94 years for the complete bearing dataset. The corresponding median corrosion-driven service life was 37.5 years for both datasets, representing the age at which 50% of bearing assemblies are estimated to have reached severe corrosion-related deterioration. The close agreement between the elastomeric-only and complete-bearing analyses suggests that the overall corrosion-driven deterioration behavior is broadly consistent across bearing types. The estimated mean and median service lives, together with their associated bootstrap standard errors, are summarized in Table 2.



(b)

Figure 5. Kaplan-Meier survival curves for corrosion-driven deterioration of bridge bearing assemblies in Maryland. (a) Elastomeric bearing assemblies only. (b) Complete bearing dataset including all bearing types.

Table 2. Kaplan-Meier estimates of corrosion-driven service life for bridge bearing assemblies.

	Age at end of service life (years)			
Bearing	Mean corrosion-driven service life	Bootstrap standard error of mean	Median corrosion-driven service life	Bootstrap standard error of median
All bearing types	36.94	0.644	37.5	1.167
Elastomeric bearing assemblies only	37.05	0.824	37.5	–

The bootstrap standard error of the median for the elastomeric-bearing subset could not be estimated because several bootstrap samples did not reach the 50% survival threshold.

2.6. Parametric Survival Modelling

A parametric survival modelling framework was subsequently employed to characterize the age-dependent deterioration behaviour of the bridge bearing assemblies subjected to corrosion-induced damage. In contrast to the nonparametric Kaplan-Meier estimator, parametric models provide a continuous functional representation of the survival distribution and enable extrapolation beyond the observed data range. Four candidate parametric survival models were considered: the Weibull, log-logistic, lognormal, and hypertabastic distributions. These models were selected due to their widespread application in infrastructure reliability analysis and their ability to represent different hazard rate behaviours (Tabatabai, Tabatabai, & Lee, 2011). Fig. 6 presents the comparison between the nonparametric Kaplan-Meier estimate and the fitted parametric survival models. All candidate models capture the general trend of declining survival probability with age; however, differences emerge at later ages, particularly in the tail behaviour.

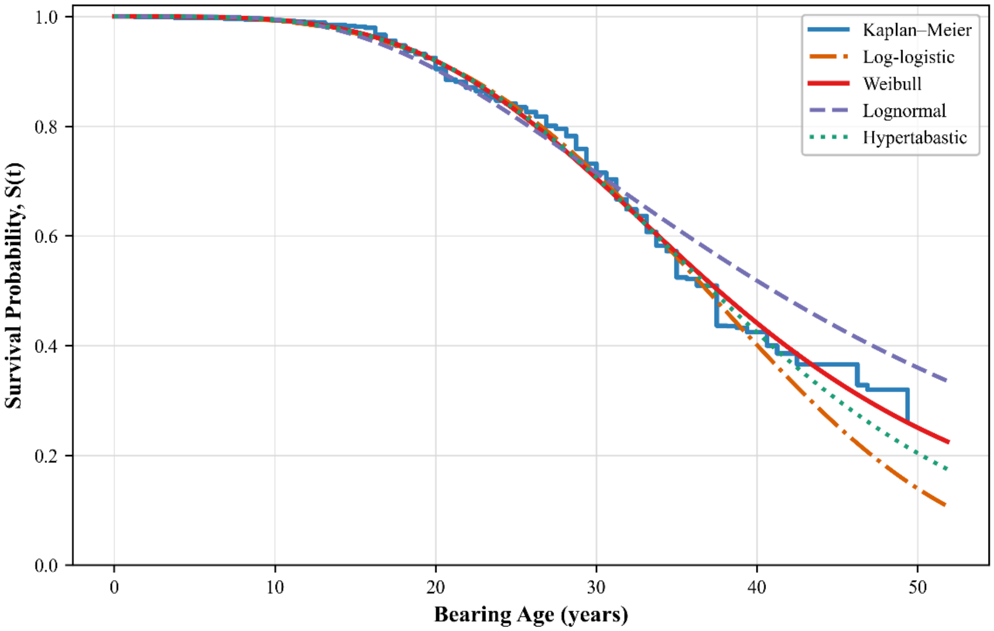


Figure 6. Comparison of nonparametric and parametric survival models for bridge bearing assembly corrosion. The Kaplan-Meier estimate is compared with fitted log-logistic, Weibull, lognormal, and hypertabastic models.

Model parameters were estimated using maximum likelihood estimation (MLE) under a weighted likelihood framework to account for varying bearing quantities across bridge records. Right-censored observations were explicitly incorporated into the likelihood function. Model performance was evaluated using the Akaike Information Criterion (AIC):

$$AIC = 2k - 2\ln(\hat{L}) \quad (2)$$

where k is the number of model parameters and $\hat{L}$ is the maximized likelihood function. The model with the lowest AIC value was selected as the preferred representation of corrosion-driven deterioration.

The AIC results summarized in Table 3 indicate that the Weibull distribution provides the best fit to the observed data among the candidate models. Specifically, the Weibull model yields the lowest AIC value (171,039.6), outperforming the log-logistic, hypertabastic, and lognormal models. In addition to its superior statistical performance, the Weibull model exhibits the closest agreement with the empirical Kaplan-Meier curve across the full age range, particularly in the region corresponding to accelerated deterioration (approximately 25-50 years).

For the Weibull model, the survival function is expressed as:

$$S(t) = \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \tag{3}$$

where t is the bearing age (years), β is the shape parameter and η is the scale parameter.

The corresponding hazard function is:

$$h(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} \tag{4}$$

The mean service life is given by:

$$E[T] = \eta\, \Gamma\left(1 + \frac{1}{\beta}\right) \tag{5}$$

where $\Gamma(.)$ is the Gamma function.

Table 3. Comparison of parametric survival models for corrosion-driven deterioration of bridge bearing assemblies in Maryland. Reported values include Akaike Information Criterion (AIC) scores and estimated model parameters.

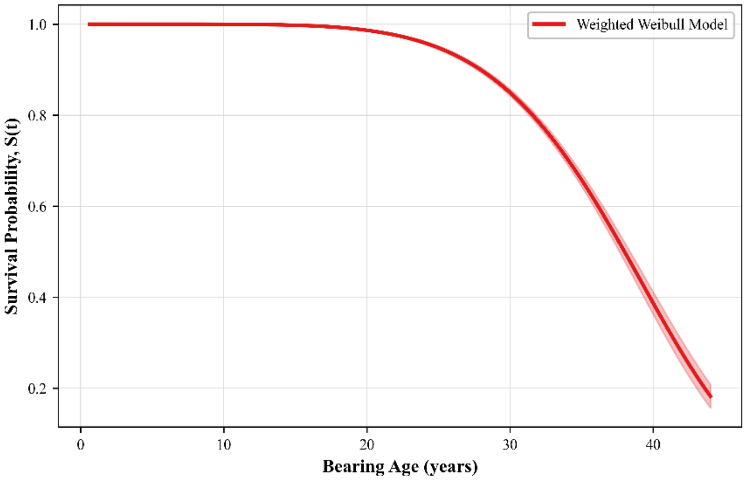
	AIC	**Model parameters**	
Weibull	171039.617	shape parameter β = 3.443	scale parameter η = 41.064
Log-logistic	171244.419	beta shape β = 3.852	alpha scale α = 37.619
Hypertabastic	171290.341	beta b = 1.85	alpha a = 0.003
Lognormal	174428.979	mu μ = 3.714	sigma σ = 0.551

Best model by AIC: Weibull

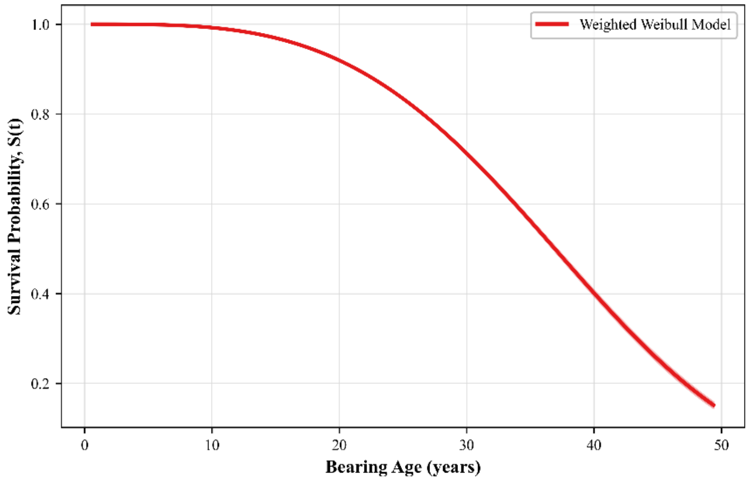
Fig. 7a and 7b illustrate the fitted Weibull survival curves for (a) elastomeric bearing assemblies only and (b) the complete bearing dataset including all bearing types, while Fig. 7c presents the corresponding Weibull hazard function for the complete bearing dataset. The fitted Weibull curves provide smooth parametric approximations of the empirical survival behaviour and capture the increasing hazard rate associated with corrosion-driven deterioration of bridge bearing assemblies.

Maximum likelihood estimation yielded Weibull shape parameters of β = 6.127 and β = 3.443, together with scale parameters of η = 40.338 years and η = 41.064 years, for the elastomeric-bearing-only dataset and the complete bearing dataset, respectively. In both cases, $\beta > 1$ indicates an increasing hazard rate, which is consistent with corrosion-driven deterioration mechanisms in which damage accumulates and accelerates over time.

However, the larger shape parameter obtained for the elastomeric-bearing-only dataset (β = 6.127) suggests a steeper late-life deterioration phase compared with the broader bearing dataset. In addition, the elastomeric-bearing-only dataset exhibited statistical instability and limited sample size, as evidenced by undefined bootstrap estimates for the Kaplan-Meier median (Table 2). Therefore, the complete bearing dataset was adopted for Weibull parameter estimation within the subsequent LCCA framework to improve statistical robustness and reduce uncertainty. The corresponding mean corrosion-driven service life predicted by the Weibull model for the complete bearing dataset was approximately 36.92 years, which is in close agreement with the Kaplan-Meier estimate. This consistency indicates that the Weibull distribution provides an appropriate parametric representation of the observed deterioration behavior. Based on its statistical performance and physical interpretability, the Weibull distribution was selected as the preferred deterioration model for the probabilistic LCCA framework. Accordingly, the fitted Weibull model with with β = 3.443, η = 41.06 years was used to probabilistically generate bearing replacement times in the Monte Carlo simulations presented in the following sections.



(a)



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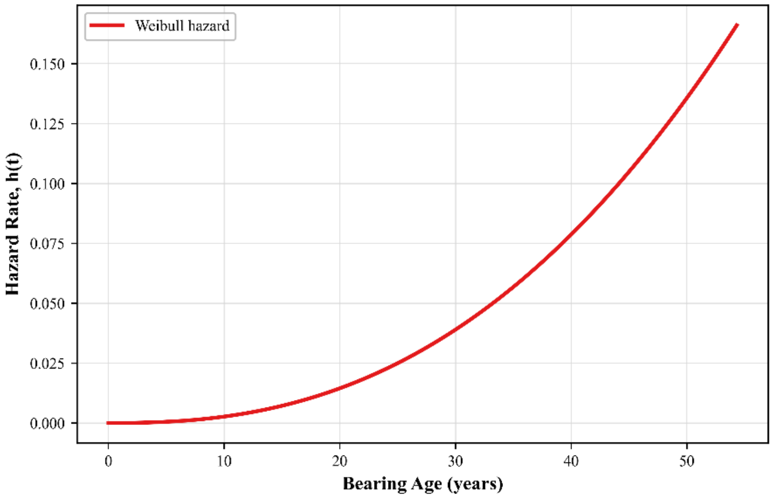


(c)

Figure 7. Weibull parametric survival and hazard functions for corrosion-driven deterioration of bridge bearing assemblies in Maryland. (a) Weibull survival model for elastomeric bearing assemblies only. (b) Weibull survival model for the complete bearing dataset including all bearing types. (c) Corresponding Weibull hazard function for the complete bearing dataset, illustrating the increasing deterioration risk with bearing age.

2.7. Discounting and Economic Assumptions

All cost estimates in the LCCA are expressed in constant (real) U.S. dollars and discounted to present value to account for the time value of money. Present-value calculations are performed using a real discount rate of 3%, consistent with commonly adopted values in transportation infrastructure economic evaluations and federal guidance documents.

The present value of a cost $C(t)$ incurred at year t is computed as:

$$\mathrm{PV}(t) = \frac{C(t)}{(1+r)^t} \tag{6}$$

where r is the real discount rate. This formulation is applied consistently to all cost components, including recurring inspection and maintenance costs and probabilistic replacement costs triggered by deterioration events.

Because long-term LCC estimates can be sensitive to discounting assumptions, alternative discount rates are examined through sensitivity analyses to assess the robustness of the results and to reflect plausible economic conditions over the bridge service life.

2.8. Monte Carlo Simulation Framework

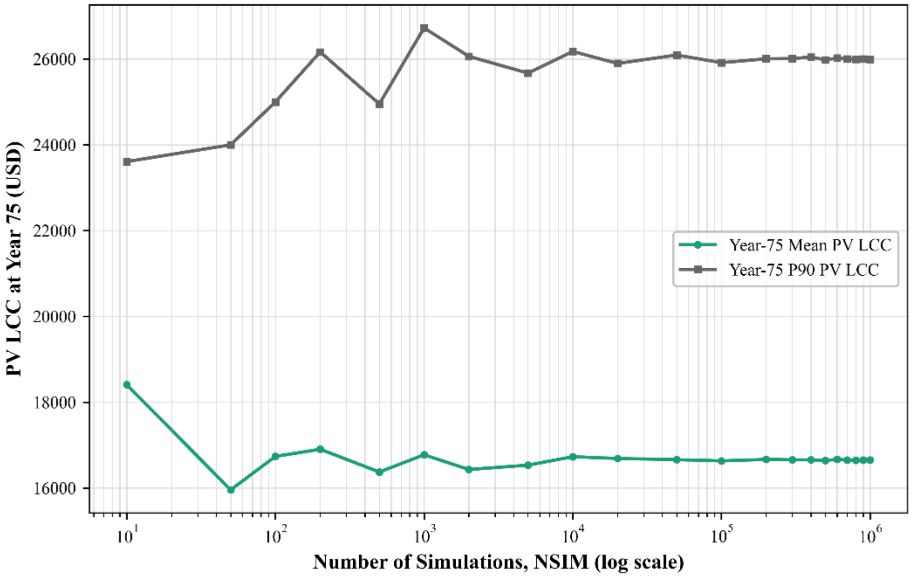
The probabilistic LCC model is evaluated using Monte Carlo simulation to propagate uncertainties associated with both cost components and replacement timing. In each simulation run, random samples are drawn from the prescribed probability distributions for all cost variables, while replacement times are sampled from the Weibull distribution representing corrosion-driven deterioration. Inspection and maintenance costs are applied at fixed two-year intervals throughout the analysis horizon, while replacement costs are incurred when the simulated failure time occurs within the service life of the bridge. All costs are discounted to present value and accumulated over the design life to obtain the total life-cycle cost for each simulation realization. A total of 1,000,000 simulation iterations are performed to ensure numerical stability and convergence of the estimated cost distributions. The ensemble of simulated cost trajectories enables the estimation of statistical summaries of LCC, including the mean, median (P50), and upper-tail (P90) values at each year of the analysis period. These metrics provide insight into both expected costs and downside financial risk, supporting risk-informed decision-making in bridge asset management.

To verify the adequacy of the selected number of simulations, a convergence analysis was conducted by evaluating the sensitivity of the Year-75 present value LCC estimates to the number of simulation iterations. As shown in Fig. 8a, both the mean and P90 estimates stabilize beyond approximately 100,000 simulations, with deviations generally below 0.5% relative to the baseline case. Increasing the number of simulations beyond this threshold results in negligible changes in the estimated metrics. Based on this analysis, a total of 1,000,000 simulations was adopted to ensure robust and converged probabilistic estimates.

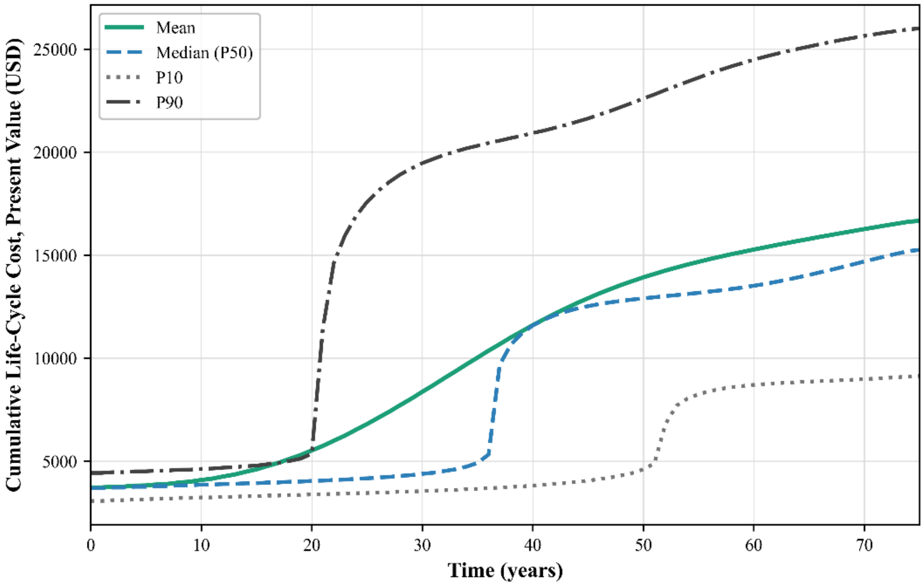
3. Results and Discussion

3.1. Baseline Life-Cycle Cost Evolution

Fig. 8b presents the baseline cumulative LCC trajectories for elastomeric bridge bearings over a 75-year analysis horizon, expressed in present value (PV, constant dollars) and obtained from 1,000,000 Monte Carlo simulations. The figure illustrates the evolution of the mean, median (P50), and selected uncertainty bounds (P10 and P90), thereby capturing both the expected cost trajectory and the dispersion arising from uncertainty in deterioration timing and cost components.



(a)



(b)

Figure 8. Monte Carlo-Based Life-Cycle Cost Evaluation of Elastomeric Bearings. (a) Convergence of Monte Carlo simulation results for Year-75 present value life-cycle cost (LCC). (b) Probabilistic evolution of cumulative LCC for elastomeric bridge bearings over a 75-year analysis horizon (present value, constant dollars).

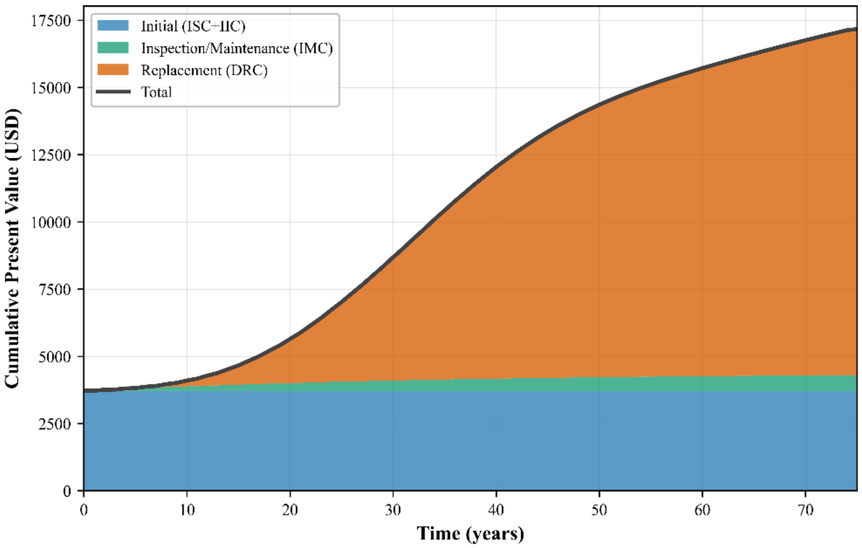
The results indicate a gradual accumulation of costs during the early service life, followed by a pronounced increase beginning approximately between 25 and 35 years. This inflection corresponds to the onset of corrosion-driven bearing replacements, as governed by the fitted Weibull deterioration model (β = 3.443, η = 41.06 years). Prior to this period, cumulative LCC is dominated by initial supply and installation costs, while inspection and routine maintenance contribute only marginally to the overall present value cost due to their relatively low magnitude and periodic nature. Beyond the first replacement phase, the rate of cost accumulation increases and exhibits divergence across probabilistic realizations. This behaviour reflects the stochastic nature of replacement timing and the high variability associated with replacement costs. The widening gap between the lower and upper percentile curves (P10 - P90) highlights the increasing uncertainty in long-term cost outcomes as the analysis horizon extends.

3.2. Interpretation of P10, Mean, and P90 Outcomes

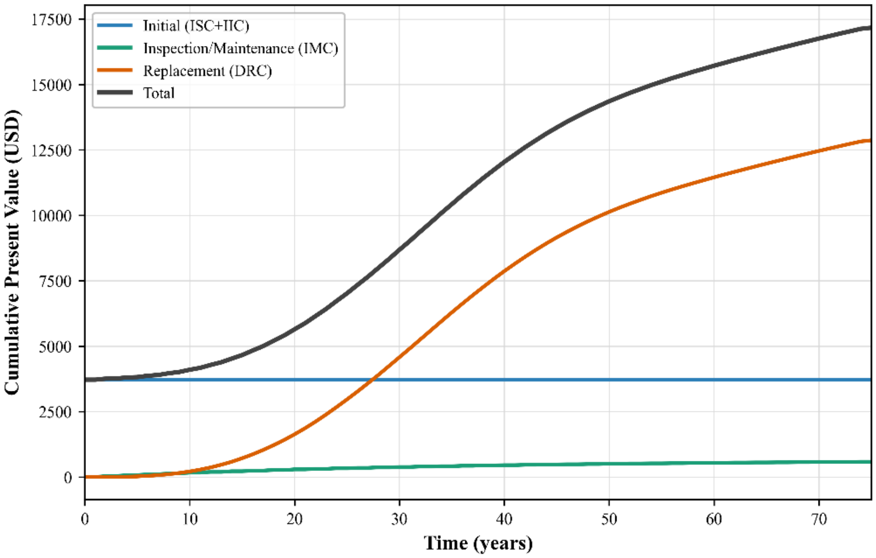
At Year 75, the baseline LCC distribution exhibits substantial spread. The mean cumulative PV LCC is estimated at \$16,663 per bearing, while the median is lower at \$15,253, indicating a right-skewed distribution driven by relatively infrequent but high-cost replacement events. While the median reflects the most typical cost realization, the mean is influenced by a subset of simulations in which early or multiple replacement events occur. This distinction has important implications for decision-making. Reliance on mean values alone may underrepresent financial risk, particularly for agencies operating under constrained budgets or risk-averse planning frameworks. The separation between the P10, mean, and P90 curves in Fig. 8 provides a direct characterization of this risk profile.

The P10 curve represents optimistic scenarios in which bearings exhibit longer service lives and/or lower-than-expected replacement costs, resulting in limited replacement activity within the analysis horizon. In contrast, the P90 curve reflects adverse but plausible scenarios characterized by earlier-than-expected deterioration and higher replacement expenditures. The lower-bound (P10) and upper-bound (P90) estimates are \$9,128 and \$25,998, respectively, suggesting that total life-cycle costs may vary by nearly a factor of three across plausible scenarios. This pronounced variability demonstrates that deterministic point estimates are insufficient for representing long-term bearing costs. Instead, probabilistic modelling is essential to capture both expected costs and the risk of high-cost outcomes. From an asset management perspective, the upper-tail estimates (e.g., P90) are particularly relevant, as they reflect conservative cost scenarios that may be used for budgeting, risk mitigation, and resilience planning.

To better understand the drivers of cumulative costs, Fig. 9 decomposes the mean PV LCC into its constituent components. Figures 9a and 9b illustrate the temporal evolution of mean cumulative PV costs by component using stacked and line representations, respectively. The results show that replacement costs dominate the life-cycle cost profile, accounting for approximately \$12,868 per bearing, or 74.9% of the total mean PV LCC at Year 75. In comparison, initial supply and installation costs contribute \$3,720 (21.7%), while cumulative inspection and maintenance costs remain relatively minor at \$583 (3.4%). This decomposition confirms that the long-term economic performance of elastomeric bearing assemblies exposed to corrosion is governed primarily by corrosion-driven replacement behaviour rather than by initial construction or routine maintenance activities. The sharp increase in total LCC observed after approximately 25-35 years is directly attributable to the onset of replacement events, which introduce large, discrete cost increments. From a practical perspective, these findings highlight that strategies aimed at extending bearing service life or reducing replacement costs, such as improved detailing, enhanced corrosion protection systems, or alternative bearing technologies, are likely to yield disproportionately large reductions in total life-cycle cost.



(a)



(b)

Figure 9. Decomposition of mean cumulative present value life-cycle cost (LCC) by component over a 75-year analysis horizon. (a) Stacked representation of cumulative cost contributions from initial costs (ISC+IIC), IMC, and DRC. (b) Corresponding line representation highlighting the temporal evolution of each cost component and total LCC.

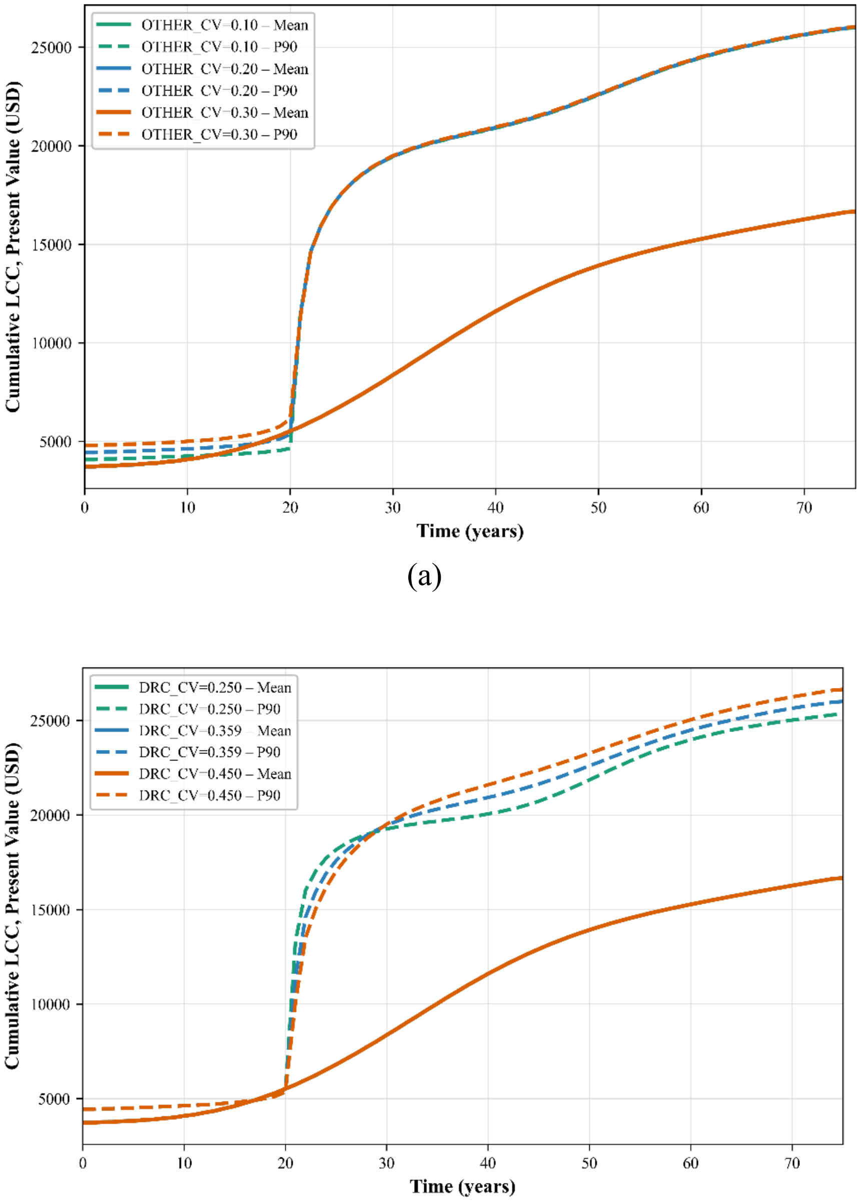
3.3. Sensitivity Results: Cost Uncertainty, Discount Rate, and Service Life

To evaluate the robustness of the LCC estimates and identify the parameters that most strongly influence long-term outcomes, three groups of sensitivity analyses were conducted: (i) cost uncertainty represented by coefficients of variation (CVs), (ii) the real discount rate, and (iii) uncertainty in corrosion-driven bearing service life as represented by the Weibull scale parameter. In all cases, sensitivity effects are evaluated using the cumulative present-value LCC at Year 75, with emphasis on both the mean and upper-bound (P90) outcomes.

3.3.1. Sensitivity to Cost Uncertainty (CV)

The first set of analyses examines the influence of cost uncertainty by varying the CV assigned to the cost components while holding all other parameters fixed. Two complementary tests were performed.

In first analysis (Fig. 10a), the coefficient of variation for direct replacement cost was held constant at its baseline value (DRC_CV = 0.359), while the CV for all other cost components (ISC, IIC, and IMC) was varied between 0.10, 0.20, and 0.30. The resulting LCC trajectories show negligible differences in both the mean and P90 curves across the three cases. At Year 75, the mean LCC remains essentially unchanged at approximately $16,663, while the P90 value varies by less than $40 across the full CV range considered. This result indicates that uncertainty in non-replacement cost components has a minimal influence on long-term LCC outcomes.



(a)

(b)

Figure 10. Sensitivity of LCC to cost uncertainty parameters. (a) Varying OTHER_CV (0.10-0.30) has negligible impact on Year-75 mean (~$16,663) and P90 (variation < $40). (b) Increasing DRC_CV (0.25-0.45) raises Year-75 P90 from ~$25,329 to ~$26,638, with minimal effect on mean LCC, indicating that replacement cost uncertainty governs upper-tail outcomes.

In second analysis (Fig. 10b), the CV for non-replacement costs was held fixed at 0.20, while the replacement cost CV was varied between 0.25, 0.359 (baseline), and 0.45. In contrast to the first sensitivity analysis, variations in DRC_CV produce a noticeable widening of the upper tail of the cost distribution. While the mean Year-75 LCC remains relatively stable, the P90 value increases from \$25,329 at DRC_CV = 0.25 to \$26,638 at DRC_CV = 0.45. This behaviour reflects the dominant contribution of replacement events to upper-bound cost outcomes and confirms that uncertainty in replacement costs primarily affects risk-averse (high-percentile) decision metrics rather than expected values. Overall, these results demonstrate that replacement cost uncertainty governs the dispersion of LCC outcomes, while uncertainty in inspection, installation, and routine maintenance costs has a negligible effect on long-term economic performance.

3.3.2. Sensitivity to Discount Rate

The influence of the real discount rate, a key parameter in long-term infrastructure economic evaluation, is examined in Fig. 11. Using baseline cost variability assumptions, the discount rate was varied between 2%, 3%, and 4%, and the resulting cumulative present value (PV) LCC trajectories were evaluated. As shown in Fig. 11, the LCC results exhibit strong sensitivity to the selected discount rate. Lower discount rates significantly increase the present value of future replacement costs, leading to higher cumulative LCC, while higher discount rates reduce the contribution of future expenditures. This effect is particularly pronounced after the onset of replacement events (approximately 25-35 years), where large future costs are introduced into the life-cycle profile.

At Year 75, reducing the discount rate from 3% to 2% increases the mean LCC from approximately \$16.6k to \$22.6k (an increase of about 36%), while increasing the rate to 4% reduces the mean LCC to approximately \$12.8k (a decrease of about 23%). A similar pattern is observed for the upper-bound (P90) metric, which increases from approximately \$26.0k at 3% to \$34.9k at 2%, and decreases to approximately \$20.1k at 4%. These results confirm that discount rate assumptions are a dominant factor in long-horizon life-cycle cost projections. For systems such as elastomeric bearings, where a large portion of total cost is associated with future replacement events, the choice of discount rate directly controls the weighting of these future expenditures. Consequently, the selection of discount rates should be carefully aligned with agency guidelines and the intended decision-making context, as it can significantly influence both expected costs and risk-informed outcomes.

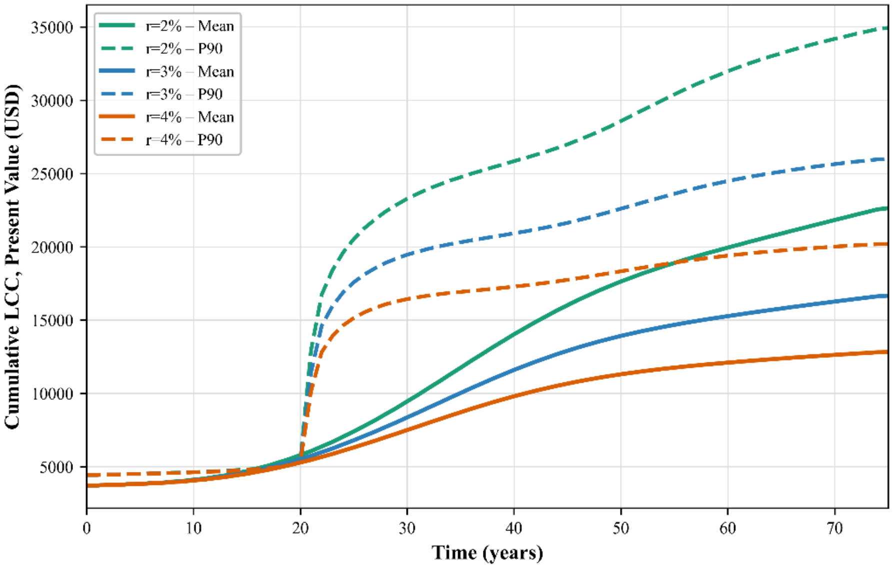


Figure 11. Sensitivity of cumulative present value life-cycle cost (LCC) to discount rate. Mean and P90 LCC trajectories are shown for real discount rates of 2%, 3%, and 4% over a 75-year horizon.

3.3.3. Sensitivity to Corrosion-Driven Service Life (Weibull H)

The influence of uncertainty in corrosion-driven bearing service life is examined by varying the Weibull scale parameter (η) while holding the shape parameter fixed (β = 3.443). Three scenarios were considered: η × 0.85, η × 1.0 (baseline), and η × 1.15, representing shorter-than-expected, nominal, and longer-than-expected corrosion-driven service lives, respectively. As shown in Fig. 12, the results reveal a strong inverse relationship between service life and LCC. At Year 75, reducing η by 15% increases the mean LCC to \$20.3 k (an increase of about 22%), while increasing η by 15% reduces the mean LCC to \$14.1 k (a decrease of about 16%). The effect is more pronounced in the upper-bound (P90) outcomes, which range from approximately \$30.7k in the low-η case to \$22.5k in the high-η case. These trends reflect the dominant role of replacement timing in life-cycle cost accumulation. Earlier failure leads to additional discounted replacement events within the analysis horizon, significantly increasing total cost, while extended service life reduces both the number and present value of replacements. Among all parameters examined, uncertainty in corrosion-driven service life emerges as one of the most influential drivers of LCC outcomes, particularly for upper-tail (risk-sensitive) metrics.

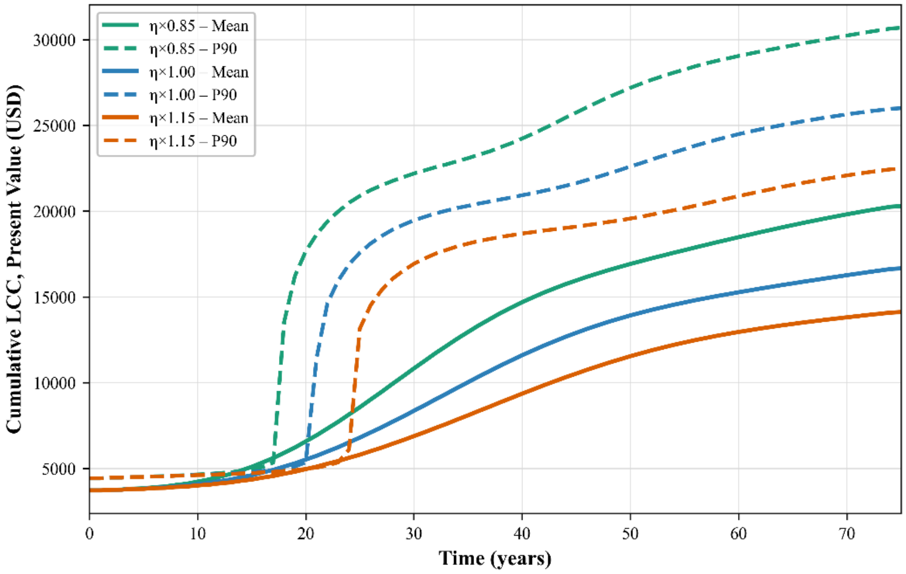


Figure 12. Sensitivity of cumulative present value LCC to corrosion-driven service life (Weibull scale parameter η). Mean and P90 LCC trajectories are shown for η × 0.85, η × 1.0, and η × 1.15.

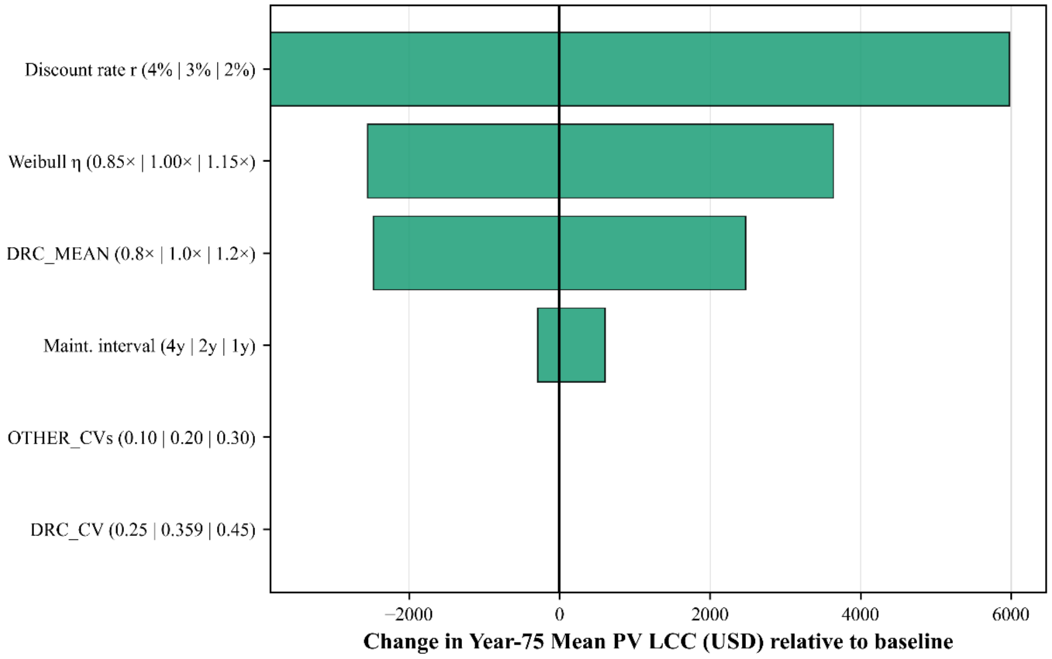
3.4. Summary of Sensitivity Findings

Taken together, the sensitivity analyses demonstrate that long-term life-cycle costs of elastomeric bridge bearings are most strongly influenced by (i) the assumed discount rate and (ii) the corrosion-driven replacement life, while uncertainty in non-replacement cost components plays a secondary role. Replacement cost uncertainty primarily affects high-percentile outcomes rather than expected values. These findings provide important guidance for agencies seeking to prioritize data collection and modelling effort, suggesting that improved estimation of bearing service life and economically appropriate discount rates will yield the greatest reductions in uncertainty in LCC assessments.

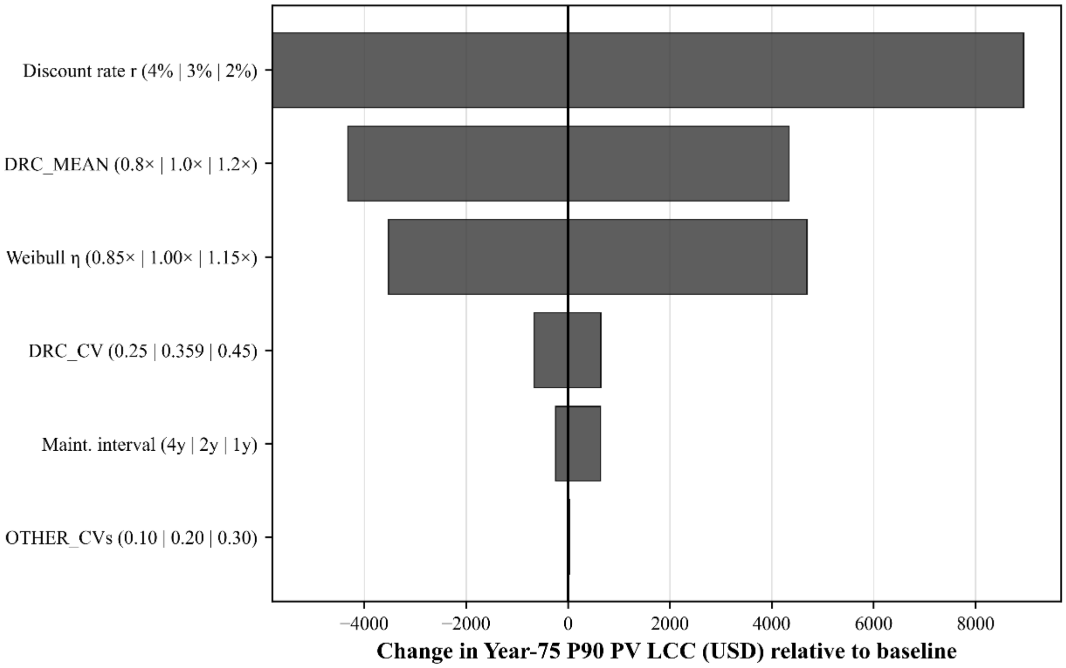
3.4.1. Tornado Sensitivity Analysis

Fig.13 presents a tornado sensitivity analysis summarizing the relative influence of key modeling assumptions on the Year-75 present-value (PV) LCC of elastomeric bridge bearings. Separate tornado plots are shown for the mean (Fig.13a) and upper-tail (P90) cost outcomes (Fig.13b), with all results expressed as deviations from the baseline scenario.

Across both metrics, the real discount rate is the dominant driver of long-term LCC variability. Varying the discount rate between 2% and 4% produces the largest swing in Year-75 costs, reflecting the strong sensitivity of long-horizon present-value estimates to discounting assumptions. This effect is especially pronounced for the P90 metric, where lower discount rates substantially amplify the present value of late-occurring replacement events. The second most influential factor is replacement timing, represented by uncertainty in the Weibull scale parameter (η). Earlier replacement timing (η × 0.85) significantly increases both mean and P90 costs by accelerating high-magnitude replacement expenditures into earlier years, while delayed replacement (η × 1.15) yields substantial cost reductions. This result highlights the importance of accurately characterizing corrosion-driven bearing service life.



(a)



(b)

Figure 13. Tornado sensitivity analysis of Year-75 present value life-cycle cost (LCC). (a) Mean LCC and (b) P90 LCC shown as deviations from the baseline.

Uncertainty in the mean replacement cost (DRC mean) ranks next in importance. A ±20% variation in the unit replacement cost leads to sizable shifts in both mean and P90 outcomes, underscoring that replacement cost assumptions are more influential than uncertainty in routine inspection or installation costs. In contrast, variations in the coefficient of variation (CV) for replacement costs and non-replacement costs (ISC, IIC, IMC) exhibit comparatively minor effects on Year-75 outcomes. Finally, changes in the inspection and maintenance interval produce only modest impacts on total LCC, indicating that routine inspection costs contribute little to long-term economic risk relative to replacement-driven expenditures. Overall, the tornado analysis demonstrates that economic assumptions (discount rate) and corrosion-driven replacement timing overwhelmingly control long-term LCC outcomes, while uncertainty in routine cost components plays a secondary role.

4. Conclusions

This study developed a data-driven framework that integrates survival analysis with probabilistic life-cycle cost analysis (LCCA) to evaluate the long-term economic performance of corrosion-affected elastomeric bridge bearing assemblies. Using large-scale inspection and element-level condition data from the FHWA NBI, corrosion-driven deterioration was characterized through both nonparametric and parametric survival modelling. Among the candidate models, the Weibull distribution provided the most appropriate representation of deterioration behaviour, capturing the increasing hazard associated with progressive corrosion damage.

The integration of the survival model within a Monte Carlo-based LCCA framework enabled explicit quantification of both expected costs and uncertainty over the bridge service life. The results demonstrate that corrosion-driven replacement behaviour governs long-term cost outcomes, with replacement-related expenditures dominating total life-cycle cost. The probabilistic analysis further highlights substantial variability in cost outcomes, underscoring the limitations of deterministic approaches and the importance of incorporating uncertainty into infrastructure economic evaluations.

Sensitivity analyses indicate that long-term cost projections are primarily influenced by discount rate assumptions and corrosion-driven service life, while uncertainty in routine inspection and maintenance costs has a comparatively minor effect. Variability in replacement costs is shown to influence upper-tail (risk-sensitive) outcomes more than mean estimates, emphasizing the need for risk-informed decision metrics in asset management.

From a practical perspective, the findings suggest that strategies aimed at extending bearing service life, such as improved corrosion protection, enhanced detailing, or adoption of corrosion-resistant bearing systems, offer the greatest potential for reducing long-term costs. More broadly, the proposed framework enables transportation agencies to integrate inspection data, reliability modelling, and economic analysis within a unified probabilistic approach, supporting more informed, transparent, and risk-aware infrastructure management decisions.

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Declaration of Interest Statement

The authors declare no conflict of interest.

Code Availability

The codes used to support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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