

Case Based Reasoning Bridge Deterioration Model

Nasser Yari¹

¹ Department of Civil Engineering Wentworth Institute of Technology, Boston, Massachusetts
E-mail: yarin@wit.edu

Published December 15, 2024

Abstract

Today's increasing average truck/vehicle miles per gallon is significantly decreasing transportation infrastructure budgets making it more difficult to sustain desirable network bridge inventories above minimum condition assessments. A bridge forecasting model is a vital part of decision making within any Bridge Management System (BMS) and the quality of decision making depends greatly on the ability to predict the future condition of bridge components accurately. The deterioration model based on artificial intelligence (AI) techniques using a Case-Based Reasoning (CBR) method was developed to support proposed GIS Based Bridge Management System (GBMS) using the data provided by New Hampshire Department of Transportation (NHDOT). CBR methodology solves new problems based on the solutions of similar past problems. The proposed model is based on the following: 1) A case library is developed based on classifications outlined in this paper, this method uses the similarity in the performance among bridges under same environmental condition, similar traffic volume, similar level of maintenance procedures within a district, analogous operating condition, and matching bridge type and material; 2) The problem bridge is evaluated to predict future deterioration rates, the system retrieval searches the database for similar case bridges then the system proceeds to a final solution.

Development and implementation of a Case-Based Reasoning (CBR) method provide states and municipalities with a tool to help identify maintenance repair, prioritize bridge rehabilitation and replacement, develop preservation strategies, and allocate available funds accordingly.

Keywords: Bridge Management, Deterioration, Bridge Components, Prediction

1. Introduction

A deterioration model is one of the minimum requirements of any Bridge Management System (AASHTO 1993). Infrastructure deterioration is caused by climatic exposure, traffic volume, insufficient financial resources, and absence of a network management system. State DOTs and municipalities are recognizing the need to implement effective tools to better manage transportation infrastructure networks and are now demanding decision-support tools (Vanier 2000). In bridge asset management, knowledge of deterioration rates is crucial for forecasting and long-term planning. Bridge deterioration is the progression of bridge components deteriorating over time due to normal operation not including natural disaster and impact damage (Chen 2022). The deterioration process due to normal aging under different environmental conditions consists of very complex

occurrences of physical and chemical changes in bridge components. Each bridge component- deck, superstructure, and substructure consists of many different elements and each element has its own unique deterioration rate (Thompson, 2001). In the early 1970s some deterioration models were developed to provide a tool for decision-makers by predicting the future condition of a pavement. This approach has been employed to develop a deterioration model for BMS (Agrawal et al, 2010).

Bridge element deterioration is caused by many different factors comprising of age, material quality environment, design characteristics, construction methods, traffic conditions etc.

A number of Probabilistic Deterioration Markov-Based Methods, both state-based and time-based, were developed in the past to forecast deterioration rate. The state-based model which forecasts long-term bridge conditions using transition

probabilities is computed from the difference between the two condition states at a given discrete time interval. The time-based model or duration model is based on element deterioration from initial state to next lower condition state. Some of the models that were developed are Markov-Based Method (Bu et al 2014), integrates state based/time-based probabilistic, and Poisson regression (DeStefano and Grivas 1998). However, these models have limitation issues such as stationary transition probability, state-independence assumption (Bu et al 2014), and failure to account for routine preventive bridge maintenance such as annual water proofing and bridge washing. Some of these models only predict the concrete bridge deck deterioration. Furthermore, the relationship between superstructure and the deck is overlooked including deck type, membrane, bridge joint, and deck geometry. This paper presents the latest advanced deterioration model for the reliable prediction of future bridge performance including deck, superstructure, and substructure.

There are approximately over 610,000 public bridges in the United States with an average age of 42 years (ASCE 2017).. The National Bridge Inventory (NBI) is the aggregation of structure inventory and appraisal data which was initially developed in 1971 to observe bridge operations and safety. The NBI inventory data consisting of 116 items provides information for each bridge. These items are specified in the Recording and Coding Guide for the structure inventory and appraisal of the Nation's Bridges (FHWA-PD-96-001). The National Bridge Inspection Standards (NBIS) were established in 1971 to require that all bridge inspection processes, frequency of inspections, qualification of the bridge inspectors, bridge inspection reports and the maintenance of bridge inventories meet the National Bridge Inspection Standards. All bridges longer than 20 feet (6.1 meters) must be inspected per (NBIS; 23 CFR 650 subpart C) and reported by the states and federal agencies to the Federal Highway Administration. Therefore, each State DOT in the United States have a large number of historical bridge-condition ratings since 1979. This massive data system can be used for CBR case library to develop an advanced deterioration model for the reliable prediction of future bridge performance. The conditions are measured visually or by using instruments based on the guidelines and standards established by the Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation Officials (AASHTO) Guide for Commonly Recognized (CoRe) Structural Elements (SE).

NBI condition ratings for various bridge components are designed based on the NBI guidelines and are listed in Appendix A. The AASHTO Guide for Commonly Recognized (CoRe) Structural Elements (SE) is an alternative to NBI condition rating. The AASHTO rating should be converted to an NBI rating using FHWA's computer program NBI translator. The FHWA National Bridge Elements (NBEs) are intended to provide consistency countrywide to standardize element condition.

Case-Based Reasoning (CBR) is an AI model developed in 1980s. Latest advancements in AI models, machine learning and

deep learning, many applications in a wide range of engineering and technology fields are utilizing the benefits of AI models. In addition, large datasets from various fields are available, and such datasets are used to train and test AI models to successfully predict outcomes with sufficient accuracy (Althaqafi 2022). The approach is solving new problems based on the solutions of similar past problems. The CBR field has grown rapidly over the past three decades and is a powerful technique for computer reasoning. CBR approach uses detailed knowledge of previous experiences and tangible problem circumstances instead of relying only on general knowledge of a problem. The primary knowledge source is not generalized rules but a memory of stored cases detailing previous experiences. A new problem is solved by finding a comparable past case and applying it to the new problem. Every time a new experience is stored, it is immediately made available for future problems. Much of the original inspiration for the CBR approach came from the role of reminding in human reasoning (Schank, 1983 and Kolodner, 1985).

The proposed deterioration model is one of the five modules that were developed to support a GIS Based Bridge Management System (GBMS). In this model, a similarity measure of classification is developed to identify how close the characteristics of bridge components are to each other based on a scoring system. There are a number of steps required to predict the future condition of an existing bridge (the problem bridge).

CBR Model

This Case-Based Reasoning systems are based on a five-step process .

1. New problem bridge evaluated for future condition rating.
2. The CBR retrieves the "most similar" case or a set of similar cases which are called proposed solutions.
3. Reuse: Utilization of information and knowledge from selected cases and adapting the solutions to address a new problem.
4. Revise: Test the new solution and revise for future use. Learning in CBR systems is by adding new cases with sufficient detail to expand the information base.
5. Retain: Store the experience gained from all new cases, to continuously upgrade the database to include the use of new materials and procedures for use in future problem solving.

Figure 1 illustrates the CBR process based on the aforementioned steps. First, a new problem (new case) is solved by the CBR program by searching the case database library for one or more recorded similar cases to the new problem. Second, the CBR program reuses the retrieved cases and selects the solution of the best-matched problem and recommends a solution to an existing problem. Third, CBR through revised process evaluates this solution between the initial problem and the retrieved cases. The revised solution is, then, evaluated for potential success and modified if necessary. Fourth, CBR approach continually expands the case database library by adding new learned cases and

supplementing existing cases when appropriate (These steps are explained in detail in later sections).

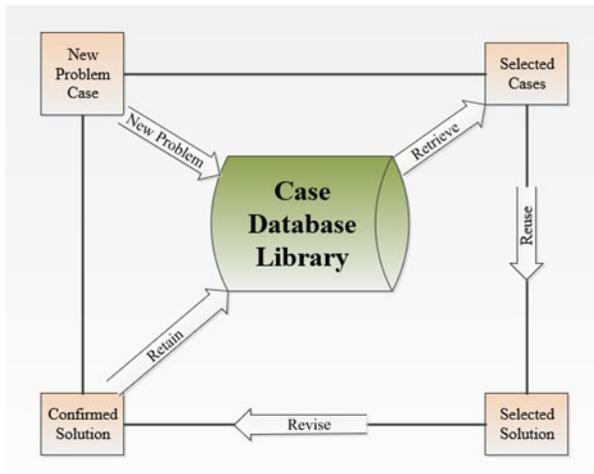


Figure 1. CBR Process.

Bridge components Case Development

The Retrieval process begins with an initial problem description and ends when best matching previous case/cases have been found. It is imperative that the CBR case library and analysis approach follows appropriate knowledge level modeling methods in defined cases, particularly the components of expertise methodology.

A similarity measure of classification is developed to identify how close the characteristics of bridge components are to each other based on scoring system values between 0 and 100, where 100 is totally similar and 0 is completely dissimilar. The CBR bridge deterioration model methodology is based on the similarity in the performance among bridges under similar environmental conditions, traffic volume, analogous operating condition, matching bridge type and material, and the equivalent level of preventive maintenance. The bridge components (deck, superstructure and substructure) case matching process is based on the following parameters for a bridge structure:

1. Bridge Structure Type, there are many different types of bridges, the most common ones in the State of New Hampshire are girder or beam type, culvert, timber, truss, and moveable.
2. Bridge Deck Types, A bridge deck is the most vulnerable component in a bridge. A severe environment, an increase in traffic volume, and aging are some of the main reasons for rapid bridge deck deterioration. There are three common materials used in the construction of bridge decks, including concrete, steel, and timber.
 - a. Concrete decks are the most common bridge deck type due to its workability to form in various shapes and sizes and are

the most flexible alternative for the bridge designer and the bridge builder; it is most adaptive to a variety of construction techniques. However, concrete being weak in tension requires reinforcement and thus receptive to corrosive deterioration. There are several common types of concrete decks including reinforced cast-in-place (CIP), precast, prestressed deck panels, and precast prestressed deck panels with a cast-in-place topping. It is very important to identify the type of rebar used on the bridge deck. Concrete with black rebar deteriorates faster than coated and stainless-steel rebar and some fiber reinforced plastics.

- b. Steel decks are composed of either solid steel plate or steel grids. There are three common types of steel decks which include corrugated steel flooring, orthotropic grid deck, and open, filled, or partially filled.

- c. Timber decks are considered non-composite. This is due to inefficient shear transfer through the attachment devices between the deck and superstructure. There are some steel bridges with timber decking. Timber is relatively easy to fabricate, and timber can also withstand significant loads over a short period of time and is locally available. There are a few basic types of timber deck, plank decks, glued-laminated deck panels, nailed laminated decks, stressed-laminated decks, and structural composite lumber decks.

3. Wearing surface is a thin layer, less than 3 inches, placed on the bridge deck to seal and protect the bridge deck from traffic and weather conditions. The basic type of wearing surface classification for each bridge deck type includes, bituminous overlay, membrane and bituminous overlay, thin overlay, rigid overlay, timber planks, concrete and serrated steel.

4. District; most DOTs are divided into small districts and each district maintains their roads and bridges, as does each municipality at different condition levels which can have a significant effect on deterioration rate and must be classified accordingly to maintenance protocol. For example, Turnpike districts wash their bridges every year while other DOT districts and municipalities never wash their bridges. A primary issue is the application of de-icing chemicals typically used in urban areas.

5. ADT; the average daily traffic is subdivided into 3 case categories. Each category is based on volume of traffic. Case category 1 being ADT > 25,000, case category 2 ADT of 10,000 to 25,000, and case category 3 with ADT < 10,000.

6. Road Classification; there are various types of roads (interstate, state routes, recreational road, town, and city streets, rural highways and unmaintained roads) within each highway network which receives different levels of maintenance.

An inspection history of over 2000 bridges provided by NHDOT is used to define cases based on the said requirements. The

inspection history with NBI condition ratings is available from late 1970s to present.

Matching Process

The case matching process is based on a scoring system value between 0 and 100 where 100 is totally similar (problem bridge is similar to the case bridge) and 0 is completely dissimilar. The matching type for bridge deck is illustrated in Table 1 and the scoring system used to define cases is shown in Table 2. The case library database for this model consists of over 2000 bridges provided by NHDOT. The matching technique from the case library is based on three categories. Over 50% of the bridges in the case library have 70% similarities and this is used as a minimum baseline. The three categories include: A) Statewide Average Case Bridge (SACB) which is a group of bridges that have a 70% or more similarities based on criteria shown in table 2. B) Average Case Bridge (ACB) includes groups of bridges with 90% similarities and C) Refined Case Bridges are ACB bridges that are within the same district and have similar roadway geometric properties.

Table 1. Bridge Deck Matching Type

Deck Type		Bridge Type	
A	Cast in place with none coated rebar		Girder
B	Cast in place with coated rebar		Timber
C	Cast in place with stainless steel rebar		Culvert
D	Precast		Truss
E	Precast Prestressed deck panels		Ridged Frame
F	Precast Prestressed deck panels with cast in place topping		
G	Corrugated steel flooring		
H	Orthotropic deck		
I	Grid Deck - open, filled, or partially filled		
J	Plank deck Timber		
K	Nailed laminated deck		
L	Glued-laminated deck planks		
M	Stressed-laminated decks		
N	Structural composite lumber decks		
Road Classification		ADT	
Tier 1	Interstates, Turnpikes, and Divided Highways	1	≥ 25000
Tier 2	Statewide Corridors	2	10000 to 25000
Tier 3	Regional Transportation Corridors	3	<10000
Tier 4	Local Connectors		
Tier 5	Local Roads		
		Wearing Surface	
		1	Membrane with Asphalt Bituminous
		2	Concrete
		3	Timber Planks
		4	Serrated steel
		District	
		1	Highway Maintenance
		2	Turnpike
		3	Municipality

Table 2. Matching Type Value

Category	SACB	ACB	RM
Matching Type	Point	Point	Point
Bridge Type	30	30	30
Deck Type	30	30	30
Wearing Surface	10	10	10
District	NA	NA	10
Road Class	NA	10	10
ADT	NA	10	10
Total	70	90	100

Case Bridge

The bridge deck deterioration rate is used to predict the future decline in the condition of the bridge deck; this information is used to prepare appropriate MR&R strategies (Kong, et al,2022).Every case bridge in the database is linked to an average case bridge. Average case bridges (ACB) are a group bridges that have 90 % or more similarities within the case bridge. The NHDOT’s bridge data is used to determine on average how many years a bridge deck remains at the various NBI condition code states. The condition rating is based on NBI specifications which were developed by FHWA (FHWA 1989). A new bridge deck typically starts at a NBI condition code of 9 and declines throughout its life. The condition rating ranges from 0 to 9, 0 being the bridge deck has failed. A 4 rating is when the bridge is classified as structurally deficient and an NBI 3 rating warrants bridge closure. The process of building the average case bridge involves analyzing each bridge inspection history. The length of time in years that a bridge deck stays at NBI condition rating increments is recorded and combined with other 90% or better similar bridges to obtain an average table 3 and 4.

Each NBI rating must go through a complete cycle which includes the beginning and end dates for each condition rating cycle. Table 3 is an example of ACB (average case bridge) which includes a group of 25 bridges with 90% similarities. All these bridges are girder type bridges with type B deck (concrete cast in place with coated rebar), tier 1 road classification. and ADT greater than 25,000. Table 4 is an example of SACB (Statewide average case bridges) which includes a group of 103 bridges that are girder bridges with type B deck and have asphaltic membrane with 2 inches of bituminous pavement for wearing surface.

Table 3. Average Case Bridge(ACB) for Type B Deck

Girder bridge Type B Deck, Membrane, Tier 1 and ADT>25 K							
NBI Rating	9	8	7	6	5	4	
Bridge 1	4	9	18				
Bridge 2	2	4	14				
Bridge 3				10	7	5	
Bridge 4	2	6			7		
Bridge 5	2	4	21				
Bridge 6	2	4	23				
Bridge 7	2	2	23				
Bridge 8	3	12					
Bridge 9	5					6	
Bridge 10	4	4				10	
Bridge 11			19				
Bridge 12		8			6		
Bridge 13		9			6		
Bridge 14	4	11	23				
Bridge 15			23				
Bridge 16	4			12			
Bridge 17				11			
Bridge 18			14	12			
Bridge 19	2	10		11			
Bridge 20			24				
Bridge 21		14					
Bridge 22					10		
Bridge 23				14	8		
Bridge 24			22				
Bridge 25	4				9		
Average(year)	3.1	7.5	20.4	11.7	7.6	7.0	
							Average expected lifespan to reach structurally deficient 57.1 Years

Table 4. Statewide Average Case Bridge (SACB) for Type B Deck

Girder bridge with concrete deck, concrete cast in place, (Type B), membrane, 2" pavement. Statewide (70)							
NBI Rating	9	8	7	6	5	4	
Bridge 1	4	8			6	14	
Bridge 2				6			
Bridge 3			24				
Bridge 4		20					
Bridge 5		18					
Bridge 6		6					
Bridge 7							
Bridge 8					12	4	
Bridge 9			20				
Bridge 10	2	16					
Bridge 11				14			
Bridge 100	2	12	12	13			
Bridge 101	1	7	6	3			
Bridge 102	2	12	16				
Bridge 103	4	24					
Average	3.25	11.51	16.54	11.58	10.00	8.71	
							Average expected lifespan to reach structurally deficient 61.6 Years

Bridge conditions are assessed by trained DOT bridge inspectors through an inspection process per National Bridge Inspection Standards (NBIS), which involves the use of specific techniques to assess the physical condition of bridges. Visual inspection is conducted on a routine or scheduled basis; however, the reliability and accuracy of the inspection can be within +/- 1 NBI rating. Because the

condition assessment of NBI rating of 8 and 7 are similar, same bridge decks can be rated 7 by one bridge inspector and 8 by another. However, combining the number of years the bridge deck condition remains at NBI 8 and 7 will result in a more accurate assessment. Analyzing the data provided by NHDOT, as illustrated in Table 3, the total years in NBI 8 and 7 is 27.9 years and from Table 4 is 28.05 years, as shown in Figure 2.

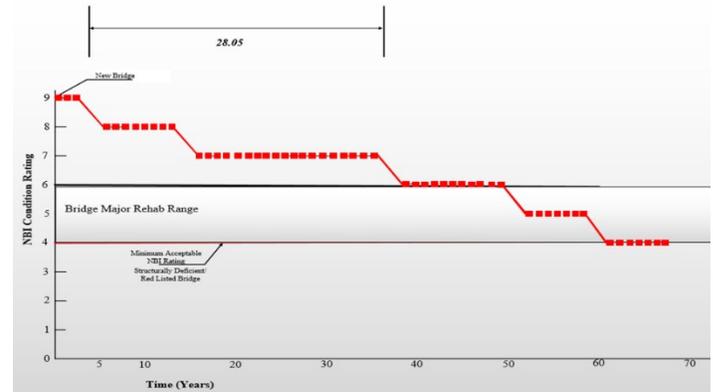


Figure 2. Deterioration Rate for Concrete CIP Deck

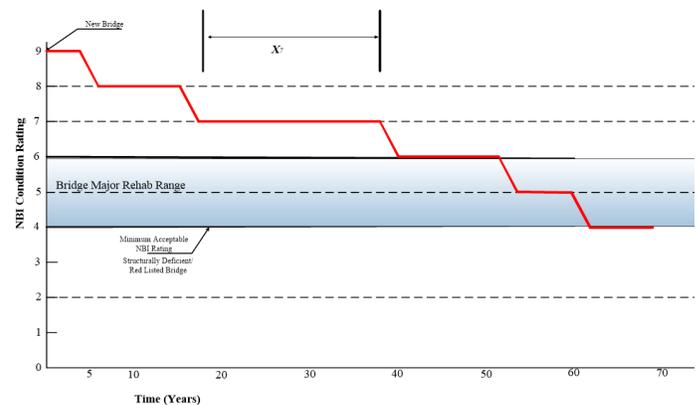


Figure 3. Average Case Bridge (ACB) Deterioration Rate for Type B Deck

Figure 3 demonstrates the deterioration rate for type B case bridge where X_i is the length of time in years that the bridge deck remains at a specific NBI condition rating.

The deterioration rate of bridge components (deck, superstructure, and substructure) is determined by the rate of deterioration between two consecutive NBI ratings calculated by the following equation:

$$D_i = \frac{CC_i - CC_{i+1}}{T_{i+1} - T_i}$$

Where,

D_i is Deterioration rate at NBI i

CC_i is Components condition rating at NBI i

T_i is Time at NBI i

Retrieval Process

The problem bridge is evaluated by the model on an individual basis and classified based on criteria shown in table 1 framework. The system retrieval will analyse the problem bridge using the matching process to search for the most similar bridge case in the case library database as outlined in Figure 4.

1. The system retrieval searches the database for ACB (bridge similarity greater than or equal to 90 points) based on the matching process. If a match is found, the system retrieval searches for a Refine Match (RM) based on condition history. The RM search on the identified ACB matches seeks bridges within a 10% differential over a designated number of years. Once RM matches are found the system continues to predict the problem bridge future deterioration rate.
2. If ACB is found and there are no RM bridges then the system proceeds to a final solution.
3. If ACB is not found, then the system will search the SACB data file through matching process to locate a matching set of bridges then proceeds to final solution.

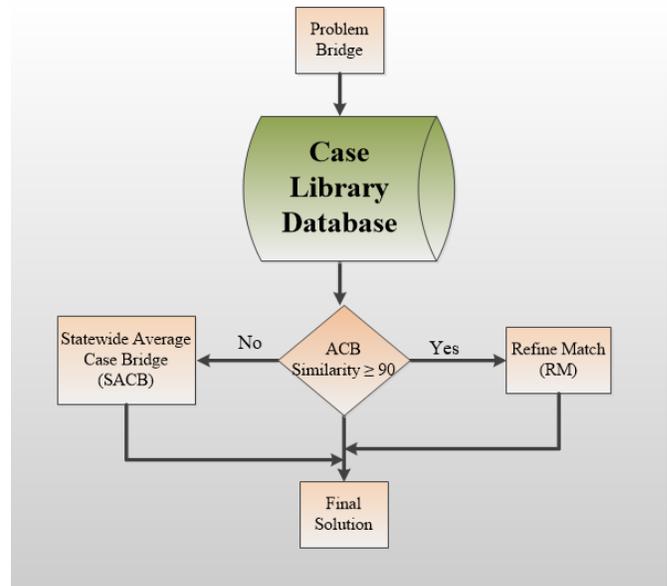


Figure 4. Retrieval Process

Example: a problem bridge (bridge # 145/060) with the given following information requires a deck condition rating be determined in 2028.

Bridge Type	Girder	NBI Rating	
Deck Type	Concrete CIP w epoxy coated rebar	1996	9
Wearing	Membrane, and 2" Pavement	1998	8
District	TPK	2000	8
Road Class	1	2002	8
ADT	> 25 K	2004	7
Year Built	1993	2006	7
		2008	7
		2010	7
		2012	7
		2014	7
		2016	7
		2018	7
		2020	7
		2022	7

Using the matching retrieval process for the given information this bridge classifies as a type B case bridge. The ACB type B is used to predict the future condition of the bridge deck. From the ACB data file there are two bridges (Bridge 5 and 6) that are very similar to the problem bridge. These two bridges are classified as Refine Match (RM).

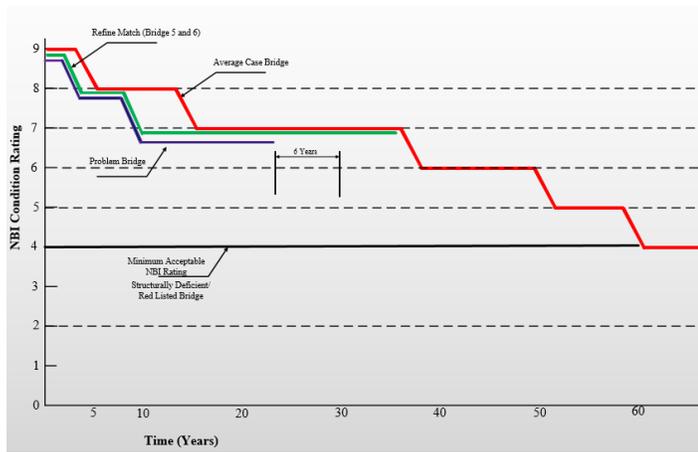


Figure 5. Problem Bridge

The Problem bridge is deteriorating at a faster rate than the average deterioration rate for the matching case bridges (Figure 5) even though the problem bridge mirrors two other bridges in the ACB file. In this case, the governing deterioration rate is the refined match (RM). The predicated condition rate for the problem bridge at age 32 is NBI 7, as shown in Figure 5.

Evaluation of Accuracy

Table 5 is one of the examples of one hundred blocks of randomly selected bridges which were used to evaluate the performance of the CBR model in terms of predicting the condition ratings of different bridge components. In this group of randomly selected bridges, the model predicted 91% accuracy for the deck, superstructure, and substructure combined based on retrieved refined match. However, the result was much different when the model couldn't find refined match. Figure 6 shows the summary of the results' percent retrieval. When a bridge was randomly selected, 73% of the time the CBR model was able to find a refined match with an average of 91% accuracy. However, if the refined match was not available, the CBR model was able to find average case bridge 93% of the time with reduced accuracy of 79%. Consequently, when both refined match and average case bridge were not available, the statewide average was available 100% of the time with low accuracy of 67%. The reason for reduced accurateness is undocumented repair work; the provided data from NHDOT has date of year built and year reconstructed. If the bridge was rehabilitated through bridge design and work was contracted out, then it is documented. However, each district maintenance has their own bridge crew for routine maintenance. Some of the repairs could be major like deck

replacement and these types of work by bridge maintenance are not documented.

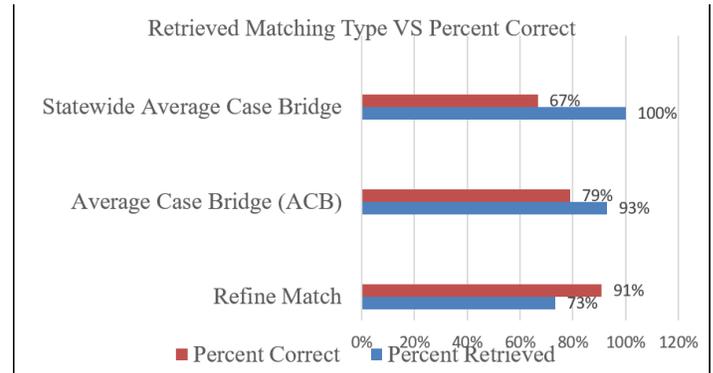


Figure 6. Accuracy Based on Retrieval Category

Table 5. Predicted Condition Vs Actual Condition

#	Bridge Number	Predicted Condition vs Actual Condition for Year 2022				Year Built	Year Rebuilt	Bridge Type	Deck Area (SF)	District
		Predicted Condition		Actual Condition						
		Deck Superstructure	Substructure	Deck Superstructure	Substructure					
1	Bartlett 120/104	7	7	7	7	1926	1986	Girder	464.1	1
2	Bath 123/070	7	7	7	7	1990		Girder	16741.4	1
3	Bedford 151/152	7	5	6	7	1964	1995	Girder	4549.9	5
4	Bedford 184/132	7	7	6	7	1959	1993	Girder	6824.4	TPK
5	Bedford 189/122	8	8	8	8	2013		Girder	18279.9	TPK
6	Bedford 195/085	8	8	8	8	2010		Girder	50093.8	TPK
7	Bedford 199/129	7	6	6	7	1960	1992-21	Girder	50309.5	5
8	Bedford 201/082	8	8	8	8	2011		Girder	4588.5	5
9	Bethlehem 099/152	7	4	6	6	1927	1998	Truss	2976.2	1
10	Bethlehem 100/050	7	7	6	7	1959	1991	Girder	3440.2	1
11	Bow 136/155	5	7	7	5	1978	2007	Girder	13142.5	TPK
12	Bow 136/158	8	8	8	8	2014		Girder	16758.7	TPK
13	Bow 136/161	7	7	7	7	1978	2002	Girder	13103.4	TPK
14	Bow 140/159	7	7	7	7	1800	1996	Girder	888.4	5
15	Brentwood 136/109	8	7	8	7	1997		Girder	6926.3	6
16	Brentwood 137/108	8	7	8	8	1997		Girder	3249.8	6
17	Brentwood 137/109	8	7	8	8	1997		Girder	7414.5	6
18	Brentwood 138/108	8	7	8	8	1997		Girder	3293.9	6
19	Bristol 097/069	6	6	7	6	1982		Girder	1142.4	2
20	Bristol 097/075	7	8	7	7	1999		Girder	2508.6	2
21	Bristol 100/082	4	4	4	4	1924	1965	Girder	1980.1	2
22	Bristol 100/095	7	7	7	7	1949		Girder	1701.2	2
23	Campton 115/126	7	7	6	7	1934	1985	Girder	634.8	2
24	Campton 117/076	6	6	7	6	1869	2014	Timber	4032.2	2
25	Campton 117/126	7	7	7	7	1900	1973	Girder	543.4	2
26	Campton 117/135	6	5	6	6	1927		Girder	2411.7	2
98	Newport 097/139	1	1	1	1	1989	-4	Girder	424.8	2
99	Newport 103/136	9	9	9	9	1937	1989	Truss	2137.3	2
100	Newport 116/142	6	6	5	6	1845	1994	Timber	1955.3	2
	Newport 129/115	6	7	7	6	1979		Girder	3485.1	2

Summary

The quality of decision making depends on the ability to accurately predict the future condition of bridge components. The deterioration process due to normal aging under different environmental conditions is a very complex occurrence of physical and chemical changes in bridge

components. To address this, a deterioration model based on the artificial intelligence (AI) technique, the case-based reasoning (CBR) method was developed. CBR methodology solves new problems based on the solutions of similar past problems. The proposed model is built on 1) The development of a case library based on classifications outlined in table 1. This method uses the similarity in the performance among bridges under analogous environmental conditions, similar traffic volume, similar level of maintenance procedures within a district, analogous operating conditions, and matching bridge type and material; 2) The evaluation of the problem bridge to project its future deterioration rates, and the system retrieval searches the database for similar Average Case Bridges (ACB). If the ACB is found, then the system retrieval searches for higher similarities and if there are none, then the system proceeds to a final solution, as shown in Figure 4. The developed deterioration model CBR is practical and uses detailed knowledge of previously experienced, tangible problem circumstances stored in the BMS library database. Every time a new experience is stored, it will be available immediately for analysing future problems. CBR has overcome the limitations of other deterioration models. The current condition state is utilized by CBR model searching through the case library database by matching the condition history, thus eliminating the uncertainty and randomness of other Markovian models. This CBR model works best with large-size networks; however, it can also be used on small networks by accessing neighbouring larger network databases.

The advantages of this method are: (1) At network level, CBR provides the BMS with reasonably accurate predictions; (2) CBR compares the current problem bridge deterioration rate with the average deterioration rates of similar bridges with the same structure type, traffic volume, maintenance level, and similar environmental and operation conditions; (3) CBR works well with a large networks by providing large database information that can be used to manage average case bridges; (4) The data from other large bridge networks can be used for smaller networks. For example, a city or town with a small network consisting of 5 to 100 bridges can use the state DOT's data or neighbouring state data since all bridge inspection history can be extracted from the NBI file. This method provides bridge deterioration rates based on their NBI condition ratings or by their structural element condition ratings. In the United States, NBI condition history for all publicly owned bridges has been available since the 1980s.

The drawbacks of a CBR system are: (1) CBR requires a large network of bridges, but as noted above, a neighbouring state or DOTs bridge data can be used; (2) In certain unique situations when a bridge structure is the first of its own type or made of new material, a matching type may not be available for use in determining the deterioration rate. In this case, the deterioration rate may be determined based on the expected lifespan recommended by the manufacture, and (3) The degree of similarity and weighting factors are based on engineering experience and judgment which can be biased.

References

1. AASHTO (1993). Guidelines For bridge management systems, American Association of State Highway and Transportation Officials, Washington, DC Washington, D. C.
2. Abed-Al-Rahim, I. and Johnston, W., (1995), "Bridge Element Deterioration Rates", Transportation Research Record, 1490, Transportation Research Board, pp.9-18.
3. Agrawal, Anil K., Akira Kawaguchi, and Zheng Chen. "Deterioration rates of typical bridge elements in New York." *Journal of Bridge Engineering* 15.4 (2010): 419-429.
4. Althaqafi, E., & Chou, E. (2022). Developing bridge deterioration models using an artificial neural network. *Infrastructures*, 7(8), 101.
5. ASCE, Reston Va, pp. 623-626.
6. Bu, G., Lee, J., Guan, H., Blumenstein, M., & Loo, Y. C. (2014). Development of an integrated
7. DeStefano, P. D., & Grivas, D. A. (1998). Method for estimating transition probability in bridge deterioration models. *Journal of infrastructure systems*, 4(2), 56-62.
8. Deterioration," Proceedings of 4th. Congress on Computing in Civil Engineering,
9. Federal Highway Administration (FHWA) (1989b), "Bridge needs and Investment process", Technical Documentation and User's Guide, U.S. Department of Transportation, Washington, D.C, version 1.2.
10. Graham, D., Smith, S. D., & Crapper, M. (2004). Improving concrete placement simulation with a case-based reasoning input. *Civil Engineering and Environmental Systems*, 21(2), 137-150.
11. Haque, M. E. (1997). Uniform Bridge element identification system for database management for roadway bridges. *Journal of Bridge Engineering*, 2(4), 183-188.

12. Kolodner, J. L., Simpson, R. L., & Sycara-Cyranski, K. (1985). A process model of case-based reasoning in problem solving (p. 6). School of Information and Computer Science, Georgia Institute of Technology.

13. Kong, X., Li, Z., Zhang, Y., & Das, S. (2022). Bridge deck deterioration: Reasons and patterns. Transportation research record, 2676(7), 570-584.

14. Kumar, H. S., & Krishnamoorthy, C. S. (1995). A framework for case-based reasoning in engineering design. AI EDAM, 9(3), 161-182.

15. Leake, D. B. (1996). CBR in context: The present and future. Case-Based Reasoning, Experiences, Lessons & Future Directions, 1-30.

16. Roddis, W. K., & Bocox, J. (1997). Case-based approach for steel bridge fabrication errors. Journal of Computing in Civil Engineering, 11(2), 84-91.

17. Schank, R. C. (1983). Dynamic memory: A theory of reminding and learning in computers and people. Cambridge university press.

18. Thompson, P. (2001), "Decision Support Analysis in Ontario's New Bridge Management System", Proceedings of the 2001 Structural Congress and Exposition, ASCE, Washington, D.C.

19. Vanier, D. J. (2000, September). Advanced asset management: tools and techniques. In Innovations in Urban Infrastructure Seminar of the APWA International Public Works Congress (pp. 39-56).

20. Wang, J. (1992). Integrated case-based reasoning for structural design.

NBI Condition Ratings		
Concrete Deck Condition Rating		
Code	Condition of Deck Item	Description of Condition
N		Use for all culverts
9	Excellent Condition	No noticeable or noteworthy deficiencies which affect the condition of the deck item. Usually new decks.
8	Very Good Condition	Minor transverse cracks with no deterioration, i.e. delamination, spalling, scaling or water saturation.
7	Good Condition	Sealable deck cracks, light scaling (less than 1/4" depth). No spalling or delamination of deck surface but visible tire wear. Substantial deterioration of curbs, sidewalks, parapets, railing or deck joints (need repair). Drains or scuppers need cleaning.
6	Satisfactory Condition	Medium scaling (1/4" to 1/2" in depth). Excessive number of open cracks in deck (5 ft intervals or less). Extensive deterioration of the curbs, sidewalks, parapets, railing or deck joints (requires replacing deteriorated elements).
5	Fair Condition	Heavy scaling (1/2" to 1" in depth). Excessive cracking and up to 5% of the deck area is spalled; 20 - 40% is water saturated and/or deteriorated. Disintegrating of deck edges or around scuppers. Considerable leaching through deck. Some partial depth failures, i.e. rebar exposed (repairs needed).
4	Poor Condition	More than 50% of the deck area is water saturated and/or deteriorated. Leaching throughout deck. Substantial partial depth failures (replace deck soon).
3	Serious Condition	More than 60% of the deck area is water saturated and/or deteriorated. Use this rating if severe or critical signs of structural distress are visible and the deck is integral with the superstructure. A full depth failure or extensive partial depth failures (repair or load post immediately).
2	Critical Condition	Some full depth failures in the deck (close the bridge until the deck is repaired or holes covered).
1	Imminent Failure Condition	Substantial full depth failures in the deck (close the bridge until deck is repaired or replaced).
0	Failed Condition	Extensive full depth failures in the deck (close bridge until the deck is replaced).

Appendix A