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Performance-based Assessment of Bridge Preservation

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PERFORMANCE-BASED ASSESSMENT OF BRIDGE PRESERVATION

BY

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ABSTRACT

Bridges all over the world are facing different problems in case of deterioration, preservation, and the cost associated with it. During the life-cycle of a bridge, diverse maintenance and repair has to be done. Depending on the geographic location, weather deterioration, traffic impacts and other hazards need to be considered. Studying the preservation strategies of the present, with focus of Rhode Island, possible improvements could be identified. Therefore, performance measures for bridge preservation are proposed. After a description of bridge deterioration for different bridge materials, bridge preservation is discussed in detail. Before the process of analyzing National Bridge Inventory (NBI) data and authoring performance measures is presented, preservation costs are described. First, the data provided needs to be processed; it is filtered to give an overview of the current state of Rhode Island bridges, using R as supporting program. Afterwards, authoring performance measures for bridge preservation is ensured by merging both NBI data and NBI element data, defining National Bridge Elements (NBEs) and Bridge Management Elements (BMEs) and putting them into relationship. Further analysis of performance measures is provided by using equations to gain cost and time information, as well as compare preservation and replacement. Finally, a preservation program is proposed which uses funding data and time intervals to enable different scenarios. The results emphasizing that preservation of bridges is more cost effective then replacement and that bridge preservation in Rhode Island is needed. A total of 27.29% of Rhode Island bridge area is at-risk to deteriorate to poor condition comparing all NBEs with all BMEs. The number of at-risk bridges with bridge joints could be reduced up to 94% with the proposed preservation program.

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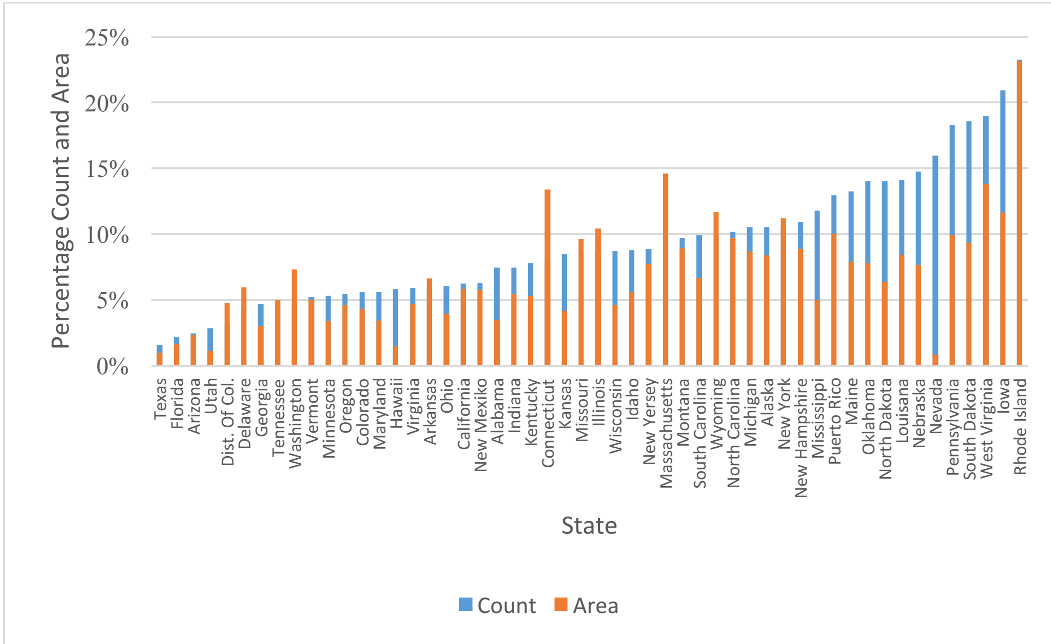
1. INTRODUCTION

Taking the smallest state of the United States, Rhode Island faces a lot of problems with bridges. There are approximately 1,162 bridges in Rhode Island (Rhode Island Statewide Planning Program 2018), of which 778 bridges are in the National Bridge Inventory (NBI) database (FHWA 2018a). Since 1972 the NBI database by the Federal Highway Association (FHWA) provides information about bridges in the United States, including type, material, construction characteristics, and more. (FHWA 2018b) The total number of bridges in RI includes every bridge which is 5 feet or longer, as defined by Rhode Island law (RIDOT 2014a). All bridges part of the NBI database are defined by the National Bridge Inventory Standards (NBIS). According to the NBIS a bridge is "a structure including supports erected over a depression or an obstruction, such as water, highway, or railway […]" and "[…] having an opening of more than 20 feet between undercopings of abutments or spring lines of arches, or extreme ends of openings for multiple boxes […]" (FHWA 1995a). Out of all 778 bridges included in the NBI about 23% (181 bridges) were classified as structurally deficient in 2017, the same percentage as for bridge area (185,131m^2) (FHWA 2017a), shown in Graph 1. That is nearly every fourth bridge in the state.



Graph 1: Structurally deficient bridges in the United States (%) (FHWA 2017b)

That makes Rhode Island ranked last of all states of the United States in case of bridge counts and bridge area, followed by Iowa and West Virginia, as shown in Graph 1. Reasons could be the geographical area of Rhode Island, as the Ocean State, with it´s high difference in temperature and heavy salt use during the winter season. Also, Rhode Island lacked preserving its bridges over the last decades and only started its preservation in 2013 (RIDOT personnel 2018).

Beginning with the Moving Ahead for Progress in the 21st Century Act (MAP-21) a 10% bridge sufficiency condition threshold for National Highway System (NHS) bridges is applied. If the deck area of NHS bridges in Rhode Island exceeds the threshold, a penalty will be applied as determined by 23 U.S.C. 119(f)(2), MAP-21 § 1106(a) (FHWA 2018c). There are 418 bridges in the NHS in Rhode Island, of which about 21% in case of bridge count (87 bridges) and about 24% (149,391m^2) in case of bridge area are structurally deficient in 2017 (FHWA 2017b). Structurally deficient bridges are not unsafe to drive on but have major deterioration, such as cracks (Rocheleau, Matt 2014). However, structurally deficient bridges need to be replaced or rehabilitated, but most importantly the remaining bridges have to be preserved to avoid that they become structurally deficient.

Rhode Island is addressing these problems with signing RhodeWorks into law on February 11, 2016 (RI.gov 2018) and pursuing the State of Rhode Island Transportation Improvement Program (STIP) (Rhode Island Statewide Planning Program 2018).

1.1. Research Goals

This study focusses on an in depth analysis of NBI data for Rhode Island to develop preservation performance measures. Therefore, the data will be retrieved, organized and analyzed.

The next chapters in this study gives sufficient knowledge about the topic in form of a literature review about deterioration (Chapter 2), preservation (Chapter 3), and cost (Chapter 4). The data analysis and methods, such as programs and equations used, are described in Chapter 5. Therein, measures are created to allow the reader to understand and analyze the preservation performance in Rhode Island. The used preservation performance measures can be used to analyze further datasets. For this, information of all previous chapters will be used. Additionally, the NBI data is connected to the previous chapters and analyzed to give the reader an overview on the current state of Rhode Island bridges. The results and discussion can be found in Chapter 6. Afterwards, conclusions can be drawn and discussed in Chapter 7.

1.2. Background

Starting in the 1960´s Maintenance, Rehabilitation and Replacement (MR&R) activities were performed as they were needed (Thompson et al. 1998). However, the collapse of the Silver Bridge, because of a fatigue cracking, and several other bridge failures brought national attention to safety issues of bridges in the United States in the late 1960´s (Small, E.P. and Cooper, J. 1998)(Small, E.P. et al. 1999). Therefore, the NBIS were developed in 1971, which prescribed mandatory inspections for deterioration, fatigue and overloading. Since 1972 the bridge inspection program collects data of conducted inspections for the NBI database (Turner, D.S. and Richardson, J.A. 1994). The first Bridge Management System (BMS) was based on NBI data (Frangopol et al. 2001). The FHWA uses the NBI information as well, for bridge management decisions regarding the state funds through the Highway Bridge Repair and Replacement Program and the Special Bridge Program (Small, E.P. et al. 1999). In the 1980´s the bridge management program BRIDGIT was the result of research initiated by the FHWA in cooperation with the National Cooperative Highway Research Program (NCHRP) (O'Conner, Daniel S. and Hyman, William A. 1989). Another program called Pontis was the result of the cooperation between the FHWA and the Departments of Transportation (DOTs) (Thompson et al. 1998). The program Pontis is the predominant bridge management program in the United States and is used by 40 state DOTs (Small, E.P. et al. 1999). In the 1990s, information about element condition, cost, traffic and historical data became more relevant and the collection of data had to be extended. The American Association of State Highway and Transportation Officials (AASHTO) hence established the Intermodal Surface Transportation Efficiency Act of 1991, which prescribed the use of a bridge management system to optimize maintenance actions for state highway agencies (AASHTO 1992). Because of the Intermodal Surface Transportation Efficiency Act of 1991 Pontis and BRIDGIT were updated in the 1990s. Now the systems can select a cost-effective option for certain budgets and prioritize needs (Frangopol et al. 2001). Through the MAP-21 Act, signed into law by President Obama on July 6, 2012 and taken into affect on October 1, 2012 (FMCSA 2014), a threshold for structurally deficient bridge deck areas is applied. The FAST Act is a five-year program passed by the Congress in December 2015, which continues the MAP-21 focus on performance management and measurement, as well as asset management (Rhode Island Statewide Planning Program 2018). With the MAP-21 Act FAST Act, bridge preservation is now eligible for federal funding (FHWA 2018d). With the enactment of MAP-21 the Highway Bridge Program (HBP) is no longer eligible for federal funds and the term functionally obsolete is no longer tracked by the FHWA for 2016 data forward (FHWA 2018a).

1.3. Bridge management systems

To maintain bridges a BMS is needed. One of the most important parts for BMSs is the collection and interpretation of data (Kim and Yoon 2010), as well as optimizing the MR&R decisions. The AASTHO also prescribed a deterioration-model as a minimum requirement of any BMS (Morcous et al. 2002). The most reliable database for bridges in the United States is the NBI. The database developed by the United States government has all the present bridge conditions (Mohammad S. Khan 2000). Every state agency, as well as the RIDOT, is participating in this program. To collect the data, the states normally inspect bridges every two years to update the NBI database and forward it to the FHWA (Kim and Yoon 2010).

To standardize bridge rating the FHWA introduced a rating scale:

Table 1: Bridge rating scale of FHWA (Kim and Yoon 2010)

Rating	Description	Technical action
9	Excellent	No action required
8	Very good	No need of repair
7	Good	Minor maintenance
6	Satisfactory	Major maintenance
5	Fair	Minor rehabilitation
4	Poor	Major rehabilitation
3	Serious	Immediate rehabilitation needed
2	Critical	Traffic to be controlled
1	Immediate failure	Bridge to be closed
0	Failed	Out of service

According to this rating scale, shown in Table 1, bridges on county levels are more structurally deficient then bridges on state level because of the lower budget and fewer engineers available. On the other hand, it was found that bridges in larger cities are less structurally deficient because they do not fit the current traffic, however, rehabilitation or replacement has been done (Kim and Yoon 2010).

Knowing these facts, bridge preservation is an important research topic. Maintenance of bridges is a long-term process. Therefore, plans and decisions have to be made based on cost and life-cycle data.

1.4. Infrequent impacts on bridges

Bridges on the east coast of the United States have to face different natural hazards, like hurricanes which have the biggest impact on cost. The impacts associated with hurricanes are wind loads, storm surge, water-borne debris impact and scour. The main impact was found to be storm surge and wave-induced loading on the bridge. During hurricanes, deck unseating is one of the most occurring failures of bridges. Because of the importance of hurricanes in bridge preservation in coastal states and the missing guidelines in the AASHTO Bridge design specifications the *Guide Specifications for Bridges Vulnerable to Coastal Storms* were developed (Mondoro et al. 2017). An additional impact on bridges which occurs infrequently are accidents. Almost half of the bridge failures between 1951 and 1988 were caused by collision that involved ships that rammed bridge supports (Dunker and Rabbat 1993). Abrupt failures not occurring due to wearing-out or deterioration can be divided into primary and secondary failures. Primary failures are induced by the unit itself, whereas secondary failures are caused by an error of secondary units (Naqib Daneshjo and Natália Jergová 2014).

2. DETERIORATION

A bridge is designed to meet certain design criterias. With time a bridge deteriorates and the bridge can collapse due to different failures. At the beginning of a bridge´s life-cycle is a high error rate due to failures in the production process, such as quality deficits in building materials or human mistakes. The failure rate decreases after early failures and increases with the bridge´s getting older and deteriorating, as Figure 1 shows (Naqib Daneshjo and Natália Jergová 2014).

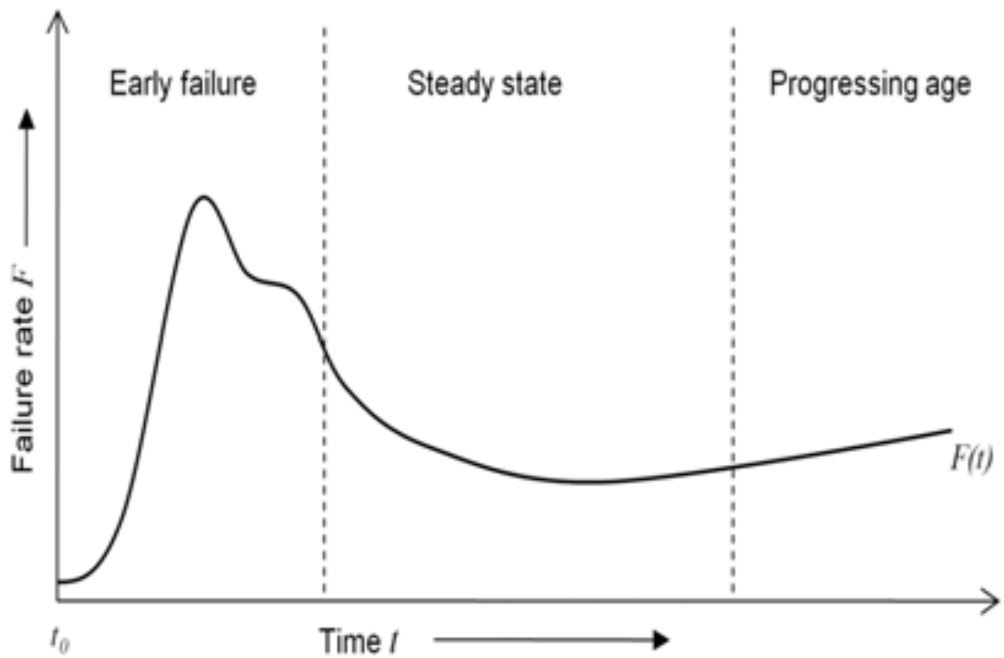


Figure 1: Typical failure rate of items (Naqib Daneshjo and Natália Jergová 2014)

A bridge deteriorates because of environmental factors and traffic loading, as shown in Figure 2 (Dunker and Rabbat 1993). In terms of traffic, the increase in loads as a result of the growing demand (Barone and Frangopol 2014), daily traffic, the structural system and number of traffic lanes (Kim and Yoon 2010). Also, larger decks deteriorate faster (Lee, Seung-Kyoung 2012b), which correlates with more traffic and lanes. Every car or truck that passes a bridge causes it to flex, whereas trucks are found to place 10 times the load of an automobile on a bridge (Dunker and Rabbat 1993). Even more if irregularities in the road surface causes the trucks to bounce and hence amplifying the stress (Dunker and Rabbat 1993).

Sources of deterioration in the context of environmental factors are corrosion, water and temperatures. Corrosion occurs from deicing salt and the contribution of rainfall or snowfall, as well as the effect of chloride (Kim and Yoon 2010). Salt solutions can rapidly corrode reinforcing bars, as well as other structural members and the concrete must be replaced when the salt content reaches a critical level even if the concrete is intact (Dunker and Rabbat 1993). Water can contribute to deterioration in several ways. Cracking of the deck is the most common bridge deterioration. Further damage can then be made by freezing and thawing of water (Wibowo and Sritharan 2018). Standing water could be accumulated because of blocked drainage systems due to debris or even the lack of a system at all, which also can lead to deterioration of concrete bridge piers. Additionally, debris can cause stresses in the superstructure if found in bridge joints because of the prevention of movement(Dunker and Rabbat 1993). Bridges over waterways face the problem with running water which removes material from the streambed. Undermining and the removal of supporting foundation material can be the result, as shown in Picture 1 (Ryan, Thomas W. et al. 2012).

Picture 1: Abutment with undermining due to scour (Ryan, Thomas W. et al. 2012)

Additionally, the exposure to extreme events (Zhu and Frangopol 2013), as well as contributing factors like age, because older bridges have a higher deterioration rate (Morcous et al. 2002), are affecting deterioration. The age of the bridge is followed by the volume of traffic and the structural system. However, the age is not as important for concrete bridges as for steel bridges in cold regions, because of the durability of concrete and cold temperatures more affecting steel bridges. (Kim and Yoon 2010).

If a bridge is deteriorating its decay is going faster because structural components under the most stress corrode faster and the stress concentration increases because the material thickness decreases. These damaged components also have reduced load-bearing capacity and are more vulnerable to heavy traffic (Dunker and Rabbat 1993).

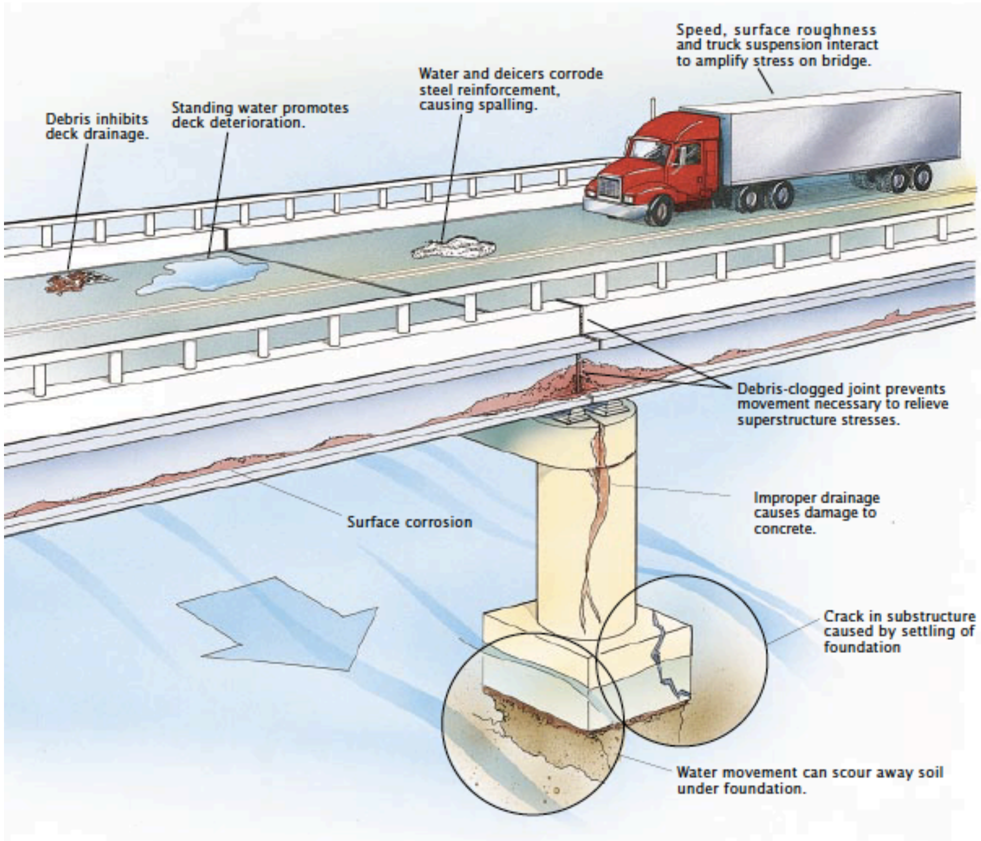


Figure 2: Sources of Deterioration (Dunker and Rabbat 1993)

This chapter, therefore, gives an overview of deterioration for different bridge materials including:

- Concrete (Chapter 2.1)
- Steel (Chapter 2.2)
- Composite (Chapter 2.3)
- Timber (Chapter 2.4)
- Stone (Chapter 2.5)

As one of the most used wearing surfaces, bituminous deterioration is briefly explained in Chapter 2.6. On the basis of each material the most important kind of deterioration is outlined, before different deterioration model approaches are outlined in Chapter 2.7.

2.1. Concrete

Taking concrete as material, there are reinforced and prestressed concrete bridges. (Lee, Seung-Kyoung 2012b) has found that the latter has grown over the last years and in 2010 around 36% of the total deck area were prestressed concrete bridges. This type of bridge is also the least vulnerable to deterioration compared to other bridge deck types, because steel bridges have a less stiff superstructure, which results in more crack than in concrete bridges (Lee, Seung-Kyoung 2012a p. 1).

However, concrete deteriorates due to different effects. An important effect for concrete structures is the deterioration through corrosion of the reinforcement induced by chloride ions penetrating through the concrete cover. As a result, the capacity of the steel reinforcement decreases. The corrosion penetration depth increases between repair and retrofit actions and therefore the probability of failure increases (Mondoro et al. 2017). Other sources of corrosion are alkali aggregate reactions and concrete carbonation (Barone and Frangopol 2014).

States in the Northeast and Midwest are heavy salt users, whereas the southern states use less salt. Deicing salt is one of the biggest chloride contributors. Therefore, the number of structurally deficient bridges is almost twice as high in the former than the latter (Lee, Seung-Kyoung 2012a p. 1). That indicates that the exposure to chloride is closely related to the deterioration of reinforced and prestressed concrete bridge decks (Lee, Seung-Kyoung 2012a). Due to corrosion in coastal regions, like Rhode

Island, the resistance of bridge members' decreases with time (Mondoro et al. 2017). Also the freezing and thawing of water needs to be considered in cold regions like Rhode Island (Kim and Yoon 2010).

That is why the biggest problem in deterioration of concrete bridges are the bridge decks and their maintenance (Kim and Yoon 2010). This is because of the direct exposure to weather, deicing salt and traffic impacts (Morcous et al. 2002).

2.1.1. Reinforced concrete bridges

Corrosion of reinforced concrete bridge decks is mainly induced by chloride ions (Lee, Seung-Kyoung 2012b p. 2), which derives from sodium chloride, the most important salt in seawater and deicing agents (Gaal 2004).

A normal corrosion process of the reinforcement, not involving chlorides, as shown in Figure 3, is an electrochemical process. The reaction product hematite and magnetite, known as rust, are formed in four steps involving anodic (at the bottom of Figure 3) and cathodic (at the top of Figure 3) reactions. The iron of the reinforcement is on the anodic site of the reaction. The iron atom loses electrons, which enter the pore water. The electrolyte is formed and takes part in the oxygen reduction. The other reaction at the cathode involves the released electrons of the anode, oxygen and water to form hydroxyl ions. The hydroxyl ions from the cathode then forms iron hydroxide with the electrolyte of the anodic reaction (in the middle of Figure 3). Iron hydroxide then sediments at the reinforcement due to its low solubility. There, it reacts with oxygen to hematite (Fe_2O_3) if sufficient oxygen is available and to magnetite (Fe_3O_4) if limited oxygen is available (Gaal 2004).

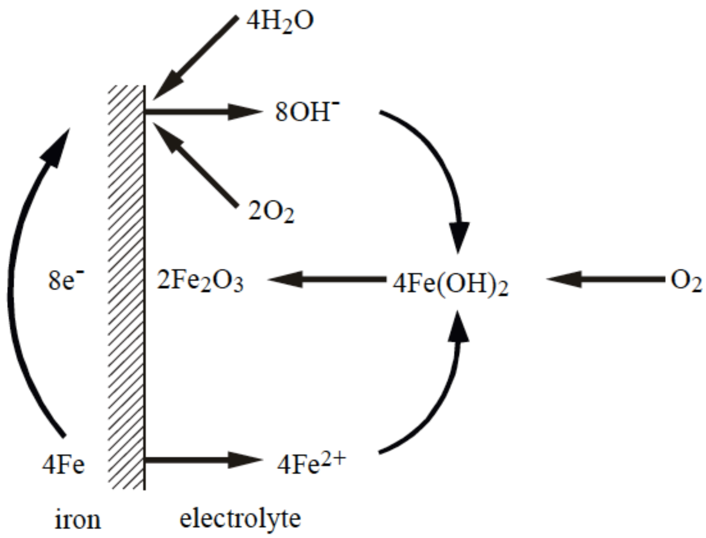


Figure 3: Corrosion process (Gaal 2004)

If chloride ions migrate into concrete through diffusion and physical defects in the concrete, the corroding rebar forms voluminous corrosion products (Lee, Seung-Kyoung 2012b p. 2). The corrosion process involving chlorides is different because the dissolved iron atoms not only react with hydroxyl ions, but also with iron to form iron chloride ($FeCl_2$). If the highly soluble iron chloride comes in contact with water, for example in corrosion pits, it reacts partially with water to form hydrochloric acid and iron hydroxide. The hydrochloric acid leads to a drop of the pH-value which accelerates the dissolution of iron (Gaal 2004). The stress arising from the corrosion of the reinforcement on the surrounding concrete then leads to cracking, delamination, and spalling of concrete, as shown in Picture 2.

Picture 2: Severe spalling at bridge pier (Gaal 2004)

Especially the spalling of underside concrete is a safety threat for underlying roadways. Like underside concrete, the deterioration of concrete decks, the superstructures and substructures of concrete bridges is mainly induced by chloride ions. Possible sources of chloride ions are seawater, splashing water that contains deicing salt, mists created by passing vehicles, and marine environments (Lee, Seung-Kyoung 2012b).

2.1.2. Prestressed concrete bridges

Comparing only the three most common bridge materials, prestressed concrete is increasing but the least used in case of superstructure material in Rhode Island. Failure due to rebar corrosion in prestressed concrete bridges is more critical because the structural integrity relies on high-strength wires and failure of a wire section is more critical than in reinforced concrete. The deterioration process of prestressed concrete bridges is nearly the same as in reinforced concrete bridges with the difference that a prestressed structure requires costly repairs if corrosion occurs (Lee, Seung-Kyoung 2012b).

Corrosion can be induced by carbon dioxide diffusion into the concrete. There, calcium hydroxide, also called portlandite, in the concrete reacts with carbon dioxide and forms calcium carbonate, which is known as carbonation. Due to the following pH reduction steel depassivation in the reinforcement occurs (Sanjuán and del Olmo 2001).

2.2. Steel

Lee, Seung-Kyoung (2012a p. 1) found that the number of steel bridges has been declining since 1992, but steel decks were still the most present deck types in 2010. Today this is Cast-in-place concrete, as shown in Graph 11 (FHWA 2018a).

The basic form of steel is iron which contains small amounts of carbon. If the carbon amount is between 0.1% and 2.1%, the material is called steel. There are also different steel types, like low carbon steel for example, which are outlined in (Ryan, Thomas W. et al. 2012).

However, steel is also used as wire, cable, plates, bars, rolled shapes and built-up shapes in bridge construction. This is because of its strength, relative ductility, and reliability. Wires are mainly used in prestressed concrete or as tendons in beams and girders. Wire ropes, parallel wires, or seven wire strands are called cables. These are used for suspension and cable-stay bridges. The difference between these bridges is that the cables on a suspension bridge are running from anchors on the earth on each side of the bridge over the towers and the bridge is suspended by secondary vertical cables from the upper cable to the bridge surface. The cables on a cable-stayed bridge are attached to the pole and the bridge surface, which are then supporting the horizontal bridge. Steel plates are used to construct built-up shapes, whereas steel bars are placed in concrete to provide reinforcement or used as secondary tension members in truss and arch bridges. Rolled shapes are made by rolling a block of steel either hot or cold. The typical shape, the "I" shape, is mainly used as structural beam and column (Picture 3) (Ryan, Thomas W. et al. 2012).

Picture 3: Rolled Beams (Ryan, Thomas W. et al. 2012)

A built-up shape on the other hand is a combination of plates, bars, and rolled shapes and are used if a rolled shape can not carry the required load or when a different shape is required which cannot be made with a rolled shape, for example I-girders (Picture 4), box girders, and truss members (Ryan, Thomas W. et al. 2012).

Picture 4: Built-up girder (Ryan, Thomas W. et al. 2012)

In comparison steel bridges are much larger, in case of bridge area, than both reinforced and prestressed concrete bridges. The rate of structurally deficient bridges has been drastically reduced over the last years, but steel is still the material most susceptible to deterioration (Lee, Seung-Kyoung 2012a). They are more affected by water then concrete bridges and the influence of cold temperatures (below 0° C or 32° F) is higher on steel bridges, whereas high temperatures (over 32° C or 90° F) are more affecting concrete bridges (Kim and Yoon 2010). Another explanation for the vulnerability of steel bridges could be their less stiffer superstructure which leads to more deck cracks, particularly transverse cracks and vibration. The two primary types of deterioration of steel bridges are:

- Coating failures (Chapter 2.2.1)
- Fatigue cracks (Chapter 2.2.2).

The latter can lead to failure of the entire structure, whereas coating failures lead to further deterioration. Further deterioration causes besides coating failure and fatigue cracking are:

- Overloading (Chapter 2.2.3)
- Corrosion (Chapter 2.2.4)

Additionally, steel can be damaged due to collision (by roadway and waterway traffic), and heat (temperatures between 400°-500°F are starting to affect strength, above 900°F steel experience a major loss of strength)(Ryan, Thomas W. et al. 2012).

2.2.1. Coating failures

Sources of coating deterioration are exposure to moisture, UV rays, mechanical damage, chemicals such as deicing salts, exposure to leaking water, debris, and salts. How fast the coating deterioration is, depends on the coating type, quality of coating application work and exposure conditions (Lee, Seung-Kyoung 2012b).

The most common coating failures also include applying too much paint, painting over surface contaminants, pinholes (tiny, deep holes in the paint, as shown in Picture 5), undercutting (mostly at sharp edges or scratches, as shown in Picture 6), bleeding (soluble color pigments from the undercoat penetrate the topcoat) and more (Ryan, Thomas W. et al. 2012).

Picture 5: Pinpoint rusting at pinholes (Ryan, Thomas W. et al. 2012)

Picture 6: Rust undercutting at scratched area (Ryan, Thomas W. et al. 2012)

2.2.2. Fatigue cracking

Fatigue cracks can cause catastrophic failures, like the Silver Bridge in West Virginia in 1967, and are occurring at a stress level below the bridge´s yield stress due to repeated loading (Dexter, Robert J. and Ocel, Justin M. 2013). A fatigue failure starts with the crack initiation, followed by crack propagation. The failure process of fatigue, which is the main cause of failure in fracture critical members, ends with sudden fracture (Ryan, Thomas W. et al. 2012). A fracture critical member can cause a portion or the entire bridge to collapse and is defined as steel member in tension (GPO 2004). The initiation is mostly at points of stress concentrations which normally are at weld flaws, fatigue prone design and fabrication details, or out-of-plane distortions. However, welded structures can not be built without some flaws and areas of high stress concentrations. If a flaw and a high stress area are combined the highest risk occurs. The propagation is then caused by cyclic stresses which cause the crack to grow until a critical size is reached (Ryan, Thomas W. et al. 2012). Relative to the propagation, the initiation is a very short period (U P and Nair 2008). The final stage of the process of a fatigue crack is a fracture, which describes the separation of an element into two pieces. If the failing element is a fracture critical member, the whole bridge can collapse (Ryan, Thomas W. et al. 2012).

2.2.3. Overloading

Overloading is becoming a more common cause for deterioration, because older bridges are not designed for todays loads. Normally steel is elastic and returns to its original shape when a load is removed. However, if a load exceeds the yield point, the steel yields and deforms permanently, which is called plastic deformation. This can occur in compression and tension members and can cause failure in the case of breaking (Tension) or buckling (Compression) (Ryan, Thomas W. et al. 2012). An unstrengthened beam could require replacement after severe overloading conditions (Dawood et al. 2007).

2.2.4. Corrosion

Corrosion is accelerated by deicing chemicals and is the primary cause of section loss in steel members and occurs as described in Chapter 2.1.1 and shown in Picture 7 (Ryan, Thomas W. et al. 2012).

Picture 7: Steel corrosion and complete section loss on girder webs (Ryan, Thomas W. et al. 2012)

However, corrosion is not only caused by deicing chemicals. Also, roadway debris, bird droppings, oxygen content, and moisture content are environmental affects that accelerate corrosion of steel in contact with soil or water (Ryan, Thomas W. et al. 2012). For example, warm water accelerates steel corrosion and steel corrodes faster in seawater than fresh water. Also, differences in pH value, temperature, oxygen, salinity within the bridge can contribute the corrosion. The part with the higher oxygen concentration then becomes the cathode and the area with lower oxygen concentration the anode (NACE International 2012).

Additionally, if an increased portion of steel at the grain boundaries is exposed due to tensile forces, the corrosion can lead to ultimate fracture and is called stress corrosion (Ryan, Thomas W. et al. 2012). Less frequent causes of corrosion can also be stray current corrosion (Electric railways, railway signal system, cathodic protection system for pipelines) (Revie and Uhlig 2008), fretting corrosion (closely fitted parts which are vibrating) (Geringer et al. 2011), bacteriological corrosion (organisms from swamps, bogs, heavy clay, contaminated water) (Permeh, S. et al. 2017), pack rust (between two mating surfaces) (Ryan, Thomas W. et al. 2012), and crevice corrosion (between adjacent surfaces) (NACE International 2012).

2.3. Composite

Most of the materials selected for a bridge are selected by short term measures instead of long-term material testing. This is why alternative materials with less maintenance requirements, improved durability and less cost over the life-cycle of a bridge are not used as much (Keoleian et al. 2005). Considering life-cycle cost fiber reinforced concrete polymer (FRP) bridge decks are emerging as alternative material (Bosman, Joel 2015). Another example is Engineered Cementitious Composite (ECC), which can improve the life-cycle of steel and concrete components in a bridge by using ECC link slabs. These can protect the deck steel girders from corrosive elements which leak through old bridge joints. Also resurfacing and maintenance of concrete bridge decks is minimized because the deterioration near the bridge joints is eliminated (Keoleian et al. 2005). More about ECC and life-cycle assessment of composite materials can be found in (Keoleian et al. 2005). Additionally, carbon fiber-reinforced polymer (CFRP) plates can be used to rehabilitate steel bridge girders (Miller et al. 2001). In conclusion, composite materials are used to minimize deterioration and this decrease the maintenance activities and cost expenditures.

2.4. Timber

There are around four percent timber bridges in the United States, of which 28.65% are built in 1950 or before (FHWA 2018a). Built because of several good physical characteristics, timber also has some negative properties (Ryan, Thomas W. et al. 2012). The two primary causes of timber deterioration are biotic agents and physical agents. The former, on the one hand, can be moisture, oxygen, temperature, insect/termite attacks, bacteria, and more. The latter, on the other hand, can be mechanical damage, chemical degradation, and more (Ritter, Michael 1990). Additionally, timber is vulnerable to fire, and excessive creep under sustained loads. Other causes of timber deterioration can be delamination and loose connections (Ryan, Thomas W. et al. 2012).

2.5. Stone

Stone bridges are seldom but partly still in use. Most of the stone bridges are made out of granite, limestone, and sandstone. Both stone and mortar properties are important when inspecting stone bridges because deterioration effects both materials. Mortar for example is not flammable but can be damaged by high temperatures. Other forms of deterioration are weathering, spalling, and splitting. Causes for theses forms are chemicals, volume changes, frost and freezing, plant / marine growth, and abrasion (Ryan, Thomas W. et al. 2012).

2.6. Bituminous wearing surfaces

Wearing surfaces with bituminous material depend on their base in case of the load-carrying capacity. That means if the base fails, the wearing surface will also fail. Reasons for failure of bituminous wearing surfaces are similar to the ones mentioned above:

- Blocked drainage systems
- Freezing and thawing
- Unsatisfactory compaction or materials
- Overloading
- Weather and age

The latter causes a hardened bituminous film, which can become brittle. The process of hardening continues during the whole life-cycle of the bitumen and is also known as oxidation with an oxidation rate. Unsatisfactory materials mean the use of poorly designed mixes or insufficient proportions of aggregate and bitumen. A different cause of bituminous wearing surface failures is bitumen stripping, which relates to aggregate that absorbs too much water and thus could separate from the bitumen. Bitumen stripping can also be caused by insufficient mixing or dirty aggregate. Overloading of wearing surface occurs if the too much soft bitumen is used, dirt is between the surface and the base, and if the placement is not done properly. Insufficient mixing and low density are also reasons for overloading to happen (Department of the Army 2000).

2.7. Deterioration model approaches

The deterioration of bridges can be modeled in different ways. Cesare et al. (1994) examines risk-based models for better inspection scheduling, whereas Morcous et al. (2002) models deterioration with case-based reasoning. Frangopol et al. (2001) analyzed the reliability-based approach. The different approaches are explained in Chapter 2.7.1. Zhu and Frangopol (2013) and Mondoro et al. (2017) examining risk-based for optimum maintenance, and Barone and Frangopol (2014) comparing the different approaches, further explained in Chapter 2.7.2.

2.7.1. Reliability-based approach and other models

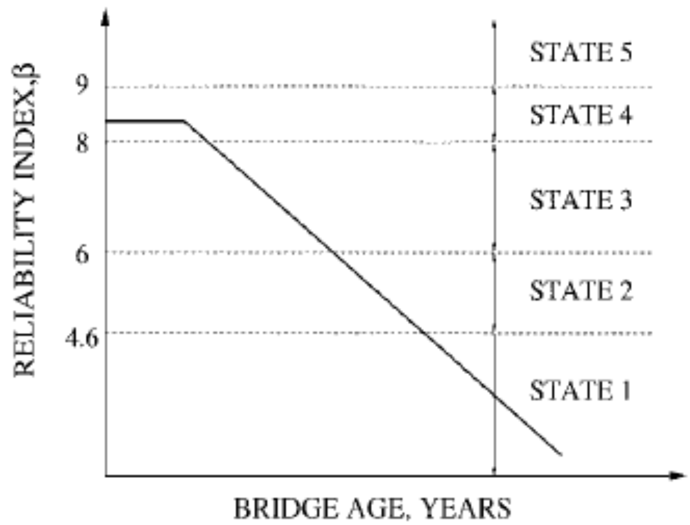
A stochastic model of deterioration of a bridge and a reliability analysis of these bridges are proposed hereinafter. To illustrate the deterioration of a bridge over time the Markov deterioration matrices could be used. With the Markovian deterioration matrices, the time until the next inspection can be predicted. To add new information gained from an inspection the Bayes theorem is used (Cesare et al. 1994).

Markovian Models are the most common stochastic models used, but there are also artificial intelligence (AI) with artificial neural networks (ANN) and case-based reasoning (CBR). CBR is a AI technique that is searching for examples from previous failures to solve the current problem. Therefore, the bridges need to be similar in case of physical features, as well as environmental and operational conditions. These examples are stored in case libraries. A CBR supports partial matching and estimates the similarities between cases. Also it can compare static, as well as dynamic data. With this approach you can run what-if analyses for different maintenance scenarios.

The success of the CBR method depends on the amount of case data, the accuracy of the data and the ability of adaptation knowledge. The system is updated while using a BMS. With the knowledge of a BMS the future condition of the bridges can be predicted (Morcous et al. 2002).

The reliability-based approach however considers all uncertainties with future reliability states, future essential maintenance or preventive maintenance, future costs and future demands. Because of this, BMSs should be reliability-based if they are run under uncertainties to overcome the limitations of condition-based approaches using the Markovian deterioration model (Frangopol et al. 2001).

Focusing on reliability-based approaches, there are five states of reliability of a bridge. The reliability index ß is time dependent and used as a measure of bridge safety. The states shown in Graph 2 are as follows: excellent (state 5, $ß \geq 9.0$), very good (state 4, $9.0 > ß \geq 8.0$), good (state 3, $8 > ß \geq 6$), fair (state 2, $6 > ß \geq 4.6$) and unacceptable (state 1, $ß < 4.6$).



Graph 2: Bridge Reliability Profile without Maintenance and Repair States (Frangopol et al. 2001)

It has to be noted that a new bridge is not always in state 5 and the linear profile represents an approximation (Frangopol et al. 2001).

But deterioration models have limitations such as the estimation of deterioration just for the no maintenance model or neglecting the uncertainty due to inherent stochasticity (Morcous et al. 2002).

Because of these uncertainties in BMSs the optimal solution might be found with a decision by the user if the optimal result is reached or if engineering judgment is needed to change the budget in the system or weighting the bridges. One uncertainty could be the relationship between reliability and the condition rating (Cesare et al. 1994).

Also a Markovian approach can not take the whole history of the bridge deterioration into account. Only single failure modes are considered, even if a bridge system depends on different components. Therefore, there are some limitations of this approach (Frangopol et al. 2001).

2.7.2. Risk-based approach

The consequences to the society, environment and economy of bridge failure can be enormous and therefore a risk-based approach is necessary. Different than a reliability-based approach, a risk-based approach is not only focused on the structure, but also on extreme events and the economic effects due to bridge failure. The goal of a risk-based approach is to maintain a bridge to keep the risk under a certain threshold. Because of limited funds the balance between the optimal maintenance strategy and low maintenance cost has to be found (Zhu and Frangopol 2013).

Risk combines the probability of occurring of the hazards, the probability of the failure due to the hazards and the consequences of this event. Because of these consequences, economic, environmental and social cost of failure can be included. The environmental cost of a bridge failure is the same considering a failure due to traffic load or a hurricane, but the economic cost of rebuilding a bridge after a hurricane failure is higher. Such bridges are susceptible to damage during coastal storms due to hydrodynamic and hydrostatic loadings generated through storm surge, waves and high wind speeds. The economic impact is the cost of rebuilding the bridge and the cost of damages of surrounding facilities caused by the failure of the bridge. The environmental and social impacts are not as easy to quantify. Environmental impacts are typically waste of construction materials or toxic gases set free during construction and failure. In case of a bridge failure the environmental impact is caused through concrete, steel and other construction materials. The social impact can be the casualties with bridge failure. The rebuilding after a hurricane of a bridge needs to be done fast to facilitate a more rapid recovery and lower the impact on the regional economy. This and the shortage of construction materials make a rebuilding of a bridge after a hurricane more expensive. The risk of that can be reduced by retrofitting and maintaining the bridge through its lifetime to decrease the probability of failure due to coastal storms. There are a lot of options to maintain a bridge with different costs associated with them. Therefore, there are two conflicting goals, minimizing the maximum life-cycle risk and minimizing life-cycle cost. For repairs and retrofits the minimizing of the life-cycle risk means a minimal increase in life-cycle cost. But solutions that might be optimal for a 50-year lifetime requirement are not always optimal for different lifetime requirements. The timing, number and type of repair and retrofit vary based on economic circumstances (Mondoro et al. 2017).

Risk assessment is the first part of a risk-based approach and can be qualitative or quantitative. Qualitative risk assessment describes the types of hazards, their likelihood and consequences and stores this information in risk matrices. Quantitative risk assessment is determining the different losses associated with failure and their costs. Risk management consists of three analyses: hazard analysis, vulnerability analysis and consequences analysis. A hazard analysis examines two different types of hazards, natural hazards (earthquakes, tornados, hurricanes etc.) or human-made hazards (fire, explosion etc.). A hazard is always uncertain and causes damage to the structure. The vulnerability analysis determines the failure probability which is the possibility that the hazard has a maximum load that exceeds the resisting capacity.

Traffic loads are the most common hazard for a bridge and for a new bridge the resisting capacity is sufficient. But with deterioration and the increase of traffic loads the probability of failure increases. Taking the vulnerability analysis, different definitions of system failure will lead to different results. After the definitions are made a vulnerability analysis is run with the computer program RELSYS. This program is used, because it is much faster than Monte Carlo simulations like CALREL or MCREL, and gives highly accurate results (Estes, Allen C. 1997). Afterwards the consequences are evaluated with three aspects: the rebuilding, running and time-loss cost. Along these three commercial losses there are also safety and environmental losses. The safety loss describes the human value which is beyond measure. An environmental loss is the cost to remove the collapsed bridge. The time-loss is associated with the bridge crossing a river, highway or railroad and these highways / railways are unavailable for a certain time and also needs to be rebuild. If the risk is under the threshold the structure is secure, if the risk is above the threshold a strategy is required to decrease the risk. Reducing the risk means reducing the probabilities of hazards, reducing the failure probabilities of the structure due to the hazards and reducing the consequences of the failure. The easiest way is to reduce the failure probability of the structure by maintenance actions (Zhu and Frangopol 2013).

But today several bridges have a significant lower structural performance due to ineffective maintenance and growing demands. To make optimal decisions in maintenance planning a probabilistic method provides the best option to handle the uncertainties due to natural phenomena, loads and structural models. Therefore, maintenance has to be done if a defined threshold is reached. A reliability-based approach is connected to the failure of the structure. However, a risk-based approach connects to direct and indirect consequences of the failure of the bridge and can be seen as the product of the failure probability and the monetary consequences. Therefore, maintenance in a risk-based approach is done with those elements having the worst consequences in case of economic, social and environmental consequences. For perfectly correlated cases the reliability-based and risk-based maintenances lead to the same results. If failure modes are not perfectly correlated, differences in the result of reliability-based and risk-based approaches can be identified. In these cases, the risk-based approach gives more attention to elements with the highest risk and therefore, the amount of repair actions over the lifetime of a bridge can be reduced (Barone and Frangopol 2014).

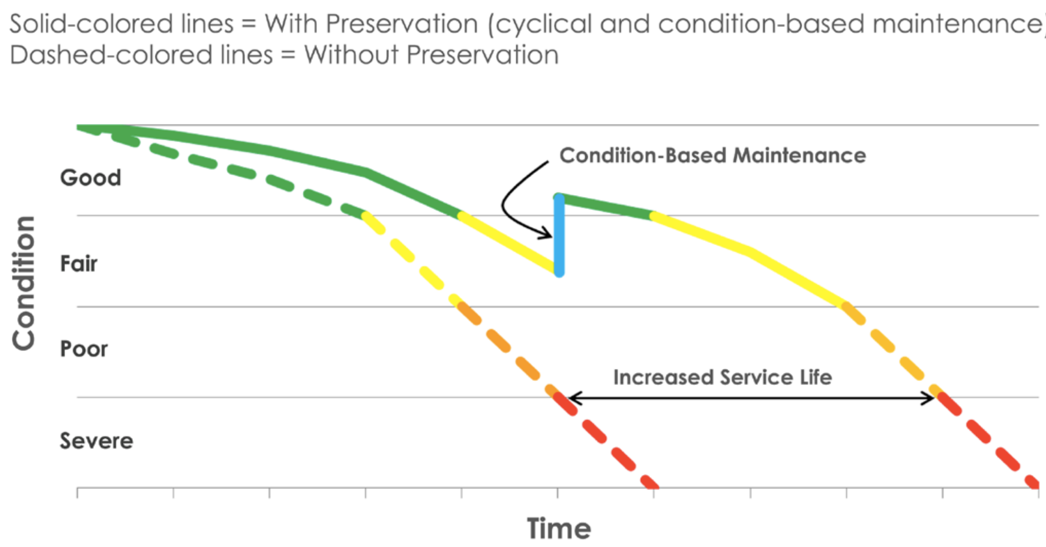
3. PRESERVATION

To preserve a bridge, the deterioration has to be decelerated. The best way to do that are preservation strategies and maintenance.

The importance of a bridge for public use is one main argument for preservation actions and more stringent design requirements. This is why bridges, which are important for public use, have a lower deterioration rate (Morcous et al. 2002).

However, it was found that the most common actions for structurally deficient bridges were the replacement of the bridge or parts of the bridge (Kim and Yoon 2010). This “worst-first” approach is not efficient. Bridge management also needs to focus on maintaining good and fair bridges, as well as using preservation, rehabilitation, and replacement strategies in a balanced way (FHWA 2018d).

In this study it has to be examined which actions are more sufficient. For this the life-cycle of a bridge, as shown in Graph 3, needs to examined.



Graph 3: A comparison of bridge condition over time with and without bridge preservation (FHWA 2018d)

Over the age of a bridge there is a wear reserve at the initial stage which decreases with time because of deterioration. At a certain time in the bridges life-cycle the bridge wears-out, if no maintenance or repair is done. Through maintenance or repair the wear reserve of a bridge increases and the life-cycle expands (Jodl, Hans Georg 2007).

According to the FHWA the bridge condition over time determines which preservation strategy has to be done, as shown in Figure 4 (FHWA 2018d).

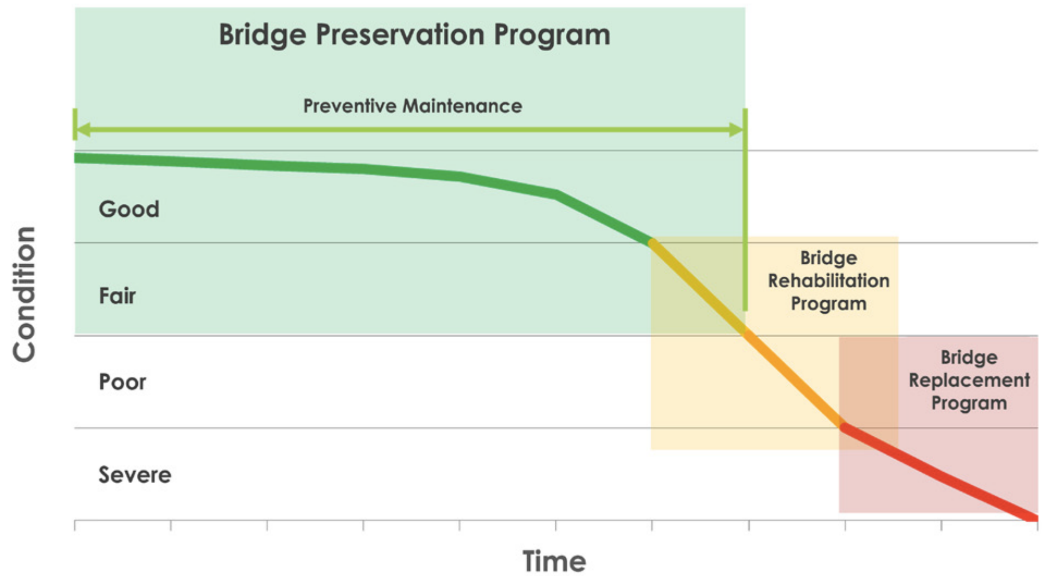


Figure 4: Bridge condition over time (FHWA 2018d)

For good bridges preventive maintenance has to be done, whereas for fair bridges it has to be decided if preventive maintenance or rehabilitation is the better strategy. Bridges in poor condition either needs to be rehabilitated or replaced and if the bridge condition is severe the only strategy is replacement (FHWA 2018d).

This chapter, therefore, gives an overview on asset management (Chapter 3.1) as basis for bridge management and preservation. For clear terminology the term maintenance (Chapter 3.2) and different kinds of maintenance are briefly defined thereafter, before preservation/preventive maintenance (Chapter 3.2.5), rehabilitation (Chapter 3.3), and replacement (Chapter 3.4) are described as part of asset management, as Figure 5 shows.

Figure 5: Bridge action categories (FHWA 2018d)

Cyclical activities and condition based activities are part of preservation/preventive maintenance. As a result, bridge preservation strategies and their outcomes are described thereafter (Chapter 3.5).

3.1. Asset management

The MAP-21 Act defines asset management as: "[…] strategic and systematic process of operating, maintaining, and improving physical assets, with a focus on both engineering and economic analysis based upon quality information, to identify a structured sequence of maintenance, preservation, repair, rehabilitation, and replacement actions that will achieve and sustain a desired state of good repair over the life-cycle of the assets at minimum cost."(112th Congress 2012) Through the MAP-21 Act, signed into law by President Obama on July 6, 2012 and taken into affect on October 1, 2012 (FMCSA 2014), asset management became an important part in bridge management (FHWA 2018d).

The implementation of an asset management plan is data driven, so a clearly identified inventory and condition assessments are necessary, as well as performance measures based on policy objectives (FHWA 2008). Asset management is done to minimize rehabilitation, as well as replacement and by this saving money over a long period of time (HNTB Corporation 2016).

3.2. Maintenance

As the word maintenance indicates, it is to maintain the condition of a bridge or transportation system and to restore the transportation system into a functional state of operation (FHWA 2017c). The DIN EN 13306:2018-02, as a European standard which serves as a guideline, describes maintenance as a "combination of all technical, administrative and managerial actions during the life-cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function" (DIN Deutsches Institut für Normung 2017). Bridge maintenance makes little or no change to bridge inventory data and includes cleaning, minor repair, major repair, component treatment, and component replacement (Hearn and Johnson 2011). Maintenance can be remote, on line, and on-site. Remote means that no direct physical access to the item is present, and on line means that maintenance is done during operating the item, whereas on-site means that the maintenance is done where the item is normally used or stored (DIN Deutsches Institut für Normung 2017). Also, maintenance is scheduled (cyclical in Figure 5) or reactive (condition-based in Figure 5) (Naqib Daneshjo and Natália Jergová 2014).

Examples for scheduled maintenance are:

- Inspections (Chapter 3.2.1)
- Routine maintenance (Chapter 3.2.2)
- Predictive maintenance (Chapter 3.2.3)
- Active maintenance (Chapter 3.2.4)
- Preventive maintenance (Chapter 3.2.5)

Examples for reactive maintenance are:

- Essential maintenance (Chapter 3.2.6)
- Corrective maintenance (Chapter 3.2.7)

At the end of this chapter strategy decisions (Chapter 3.2.8) are briefly defined.

3.2.1. Inspections

To make a decision on maintenance, rehabilitation and repair (MR&R), as well as Essential Maintenance (EM) and Preventive Maintenance (PM) options, you have to predict the future of a bridge (Morcous et al. 2002). To better predict the future of a bridge and their conditions, several types of inspections have to be made. Inspections and their interval are depending on the type of bridge or component, its condition rating, the deterioration rate and the selected inspection criterion. Several inspection intervals should be established to optimize the overall inspection because different elements have different inspection intervals (Cesare et al. 1994). Inspections are made to determine, evaluate, and assess the actual state, as well as to initiate further measures. As a result, the wear-out of a unit can be monitored and reasons can be recognized, which makes planning maintenance activities possible (Naqib Daneshjo and Natália Jergová 2014).

The RIDOT does inspection on element level and depending on the condition of a bridge. The NBIS prescribes a routine inspection at least every two years. Non-NBI bridges in Rhode Island are also inspected every two years or if in good condition every 4 years. However, if a bridge is in poor condition there can be a monthly inspection interval (RIDOT personnel 2018).

Table 2: Bridge condition/classification and frequency level (Baker, Michael and RIDOT 2013)

Bridge Condition/Classification	Frequency (months)
Fracture Critical	12
Posted	12
Closed	12
Temporarily Supported	12
Underwater	60
Seismic	Not Performed
Special	3 to 12
Routine/All Other	24

Table 2 **Fehler! Verweisquelle konnte nicht gefunden werden.**shows the inspection frequency depending on the bridge condition or classification. Nevertheless, most of the bridges are inspected every 24 months regarding a routine inspection. Bridge inspections for fracture critical, posted, closed, and temporarily supported bridges are every 12 moths, whereas special inspection are every 3 to 12 months, and underwater inspections every 60 months (Baker, Michael and RIDOT 2013).

To manage inspections and their intervals a management system is needed, as described in Chapter 3.5.5.

3.2.2. Routine maintenance

Routine maintenance, as a part of maintenance, is performed after a certain event, during a season, or for short-term needs without preservation value.

Picture 8: Bridge snow removal (FHWA 2018d)

Examples for routine maintenance are snowfall/application of deicing salt, trash/litter/dead animal removal, graffiti removal, accidents and storm damage, and asphalt patching.

As per MAP-21 act routine maintenance is not eligible for federal funding, which means that states have to pay for damages occurring through the examples mentioned, among other things (FHWA 2018d).

3.2.3. Predictive maintenance

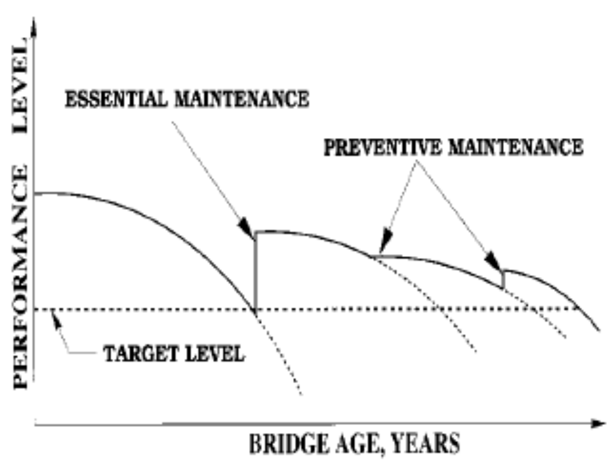
The DIN EN 13306:2018-02 describes predictive maintenance as "condition-based maintenance carried out following a forecast derived from repeated analysis or known characteristics and evaluation of the significant parameters of the degradation of the item" (DIN Deutsches Institut für Normung 2017). This kind of maintenance is also done by the RIDOT by applying maintenance actions on a time based schedule created on the basis of a deterioration model (RIDOT personnel 2018).

3.2.4. Active maintenance

Active maintenance is a “part of maintenance where actions are directly carried out on an item in order to retain it in, or restore it to a state in which it can perform the required function” (DIN Deutsches Institut für Normung 2017). This could mean that actions are directly taken after a degradation is observed. Therefore, active maintenance is to restore an item (DIN Deutsches Institut für Normung 2017).

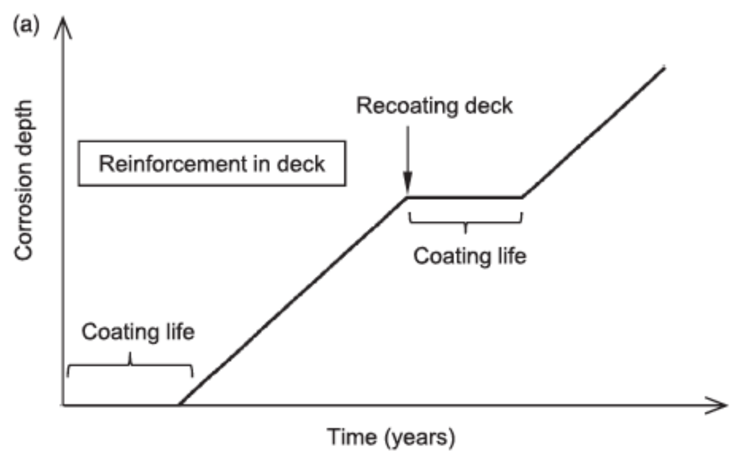
3.2.5. Preventive maintenance

As shown in Graph 3 a bridge has a certain wear reserve and deteriorates over time. The same effect shows Graph 4, except that the maintenance is now divided into PM and EM (Frangopol et al. 2001).

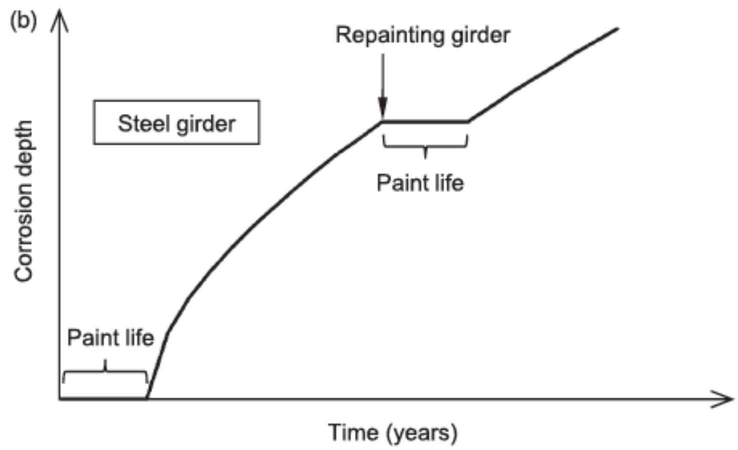


Graph 4: Whole Life Bridge Performance as Affected by Essential and Preventive Maintenance (Frangopol et al. 2001)

PM is time-based and therefore done due to a fixed schedule (Zhu and Frangopol 2013). The DIN EN 13306:2018-02 describes PM as “maintenance carried out intended to assess and/or mitigate degradation and reduce the probability of failure of an item” (DIN Deutsches Institut für Normung 2017). PM actions consists of repair, such as repainting, recoating and waterproofing. As the Graph 5 and Graph 6 are illustrating, painting and coating are done to protect the structure from corrosion and thus extending the life-cycle of the bridge. After the service life of the painting or coating the corrosion of the steel girders or reinforcement in the concrete begins.´ (Zhu and Frangopol 2013).



Graph 5: Effect of PM option: Recoating the Deck (Zhu and Frangopol 2013)



Graph 6: Effect of PM option: Repainting the Girder (Zhu and Frangopol 2013)

Furthermore, there are also two types of PM actions:

- Proactive
- Reactive

Proactive PM is done before a member deteriorates, reactive after a member deteriorated. The former is done to delay the initiation time of deterioration ,the latter to slow down the deterioration of the structure (Zhu and Frangopol 2013). A description in the DIN EN 13306:2018-02 close to reactive maintenance is predetermined maintenance: “preventive maintenance carried out in accordance with established intervals of time or number of units but without previous condition investigation” (DIN Deutsches Institut für Normung 2017). Also, the description of condition-based maintenance in DIN EN 13306:2018-02: “preventive maintenance which include assessment of physical conditions, analysis and the possible ensuing maintenance actions” (DIN Deutsches Institut für Normung 2017).

PM actions also can be done in non-uniform and uniform time intervals, whereas non-uniform intervals are found more economical (Zhu and Frangopol 2013).

3.2.6. Essential maintenance

EM, as reactive maintenance, describes an action which is done if the performance indicator is close to or reaches the defined threshold. EM actions can be the repair or replacement of parts to improve the whole structure (Zhu and Frangopol 2013). Also, EM depends on the structural condition of an existing bridge and has a higher environmental impact. However, EM actions are improving the bridge reliability (Xie et al. 2018).

3.2.7. Corrective maintenance

Maintenance which is carried out after a fault is recognized and to restore the item into a state in which it can perform a certain function is called corrective maintenance. Corrective maintenance can be done deferred or immediate. The latter is to avoid unacceptable consequences and the former to delay the maintenance under given rules (DIN Deutsches Institut für Normung 2017).

3.2.8. Strategy decisions

The decision for a EM strategy depends on the budget, as well as the attitude towards risk of the decision maker, because the EM strategy that keeps the bridge at a lower risk costs more money. The total costs of PM strategies are found much less than with EM strategies (Zhu and Frangopol 2013). The RIDOT also decides on the basis of their asset management, which means that the life-cycle, condition, financials and time are important factors. Also the structural condition, environmental permitting, historic preservation issues, load posting, structure type, deterioration rate, public input, and more are important factors (Rhode Island Statewide Planning Program 2018) It needs to be evaluated if the preservation strategy adds enough value to a bridge which already exceeded its design life (RIDOT personnel 2018).

3.3. Rehabilitation

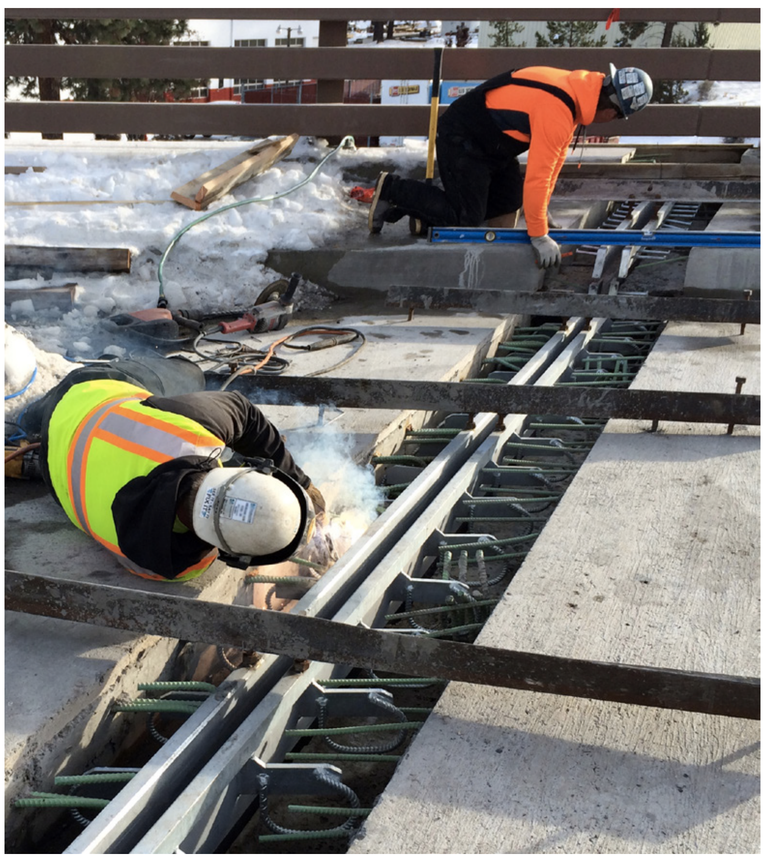
Rehabilitation is done if the structural integrity of a bridge has to be restored. This requires major work such as partial or complete deck replacement, superstructure replacement, and substructure/culvert strengthening or partial/full replacement.

Picture 9: Substructure repair (FHWA 2018d)

Rehabilitation is also done to correct major safety defects and is the complete or nearly complete restoration of bridge elements (FHWA 2018d).

3.4. Replacement

Replacement is done if rehabilitation would not add enough value to the bridge and if the strategy is to replace a bridge instead of preserving it. Total replacement of a bridge needs engineering work to meet the current geometric, structural, and construction standards. Replacement of a bridge part, like joint replacement, is done if the rest of the bridge is still in a condition worth keeping (FHWA 2018d).



Picture 10: Joint replacement (FHWA 2018d)

3.5. Preservation activities and outcomes

In this study preservation strategies are considered as PM and EM actions. Rehabilitation and replacement are actions which are going beyond the preservation strategy. Therefore, rehabilitation and replacement actions are briefly mentioned but the focus for this study lies on maintenance. The preservation activities are ordered by bridge sections:

- Bridge decks (Chapter 3.5.1)
- Superstructure (Chapter 3.5.2)
- Substructure (3.5.3)

As a result of compiling bridge preservation activities, the

- RIDOT strategies and activities (Chapter 3.5.4)
- AASHTOWare Bridge Management (Chapter 3.5.5)

are described thereafter.

3.5.1. Bridge deck protection

Rhode Island and the United States are not using a protection for bridge decks in the most cases by bridge count (39.64% in Rhode Island, 54.49% in the United States are not using a bridge deck protection) (FHWA 2018a). Bridge deck protections can be epoxy coated reinforcement, galvanized reinforcement, other coated reinforcement, cathodic protection, polymer impregnated, internally sealed, and more (GPO 2004). In around 20% of the cases in Rhode Island it is unknown if a deck protection is used. For the United States this percentage is 11.26%. If a deck protection is used, epoxy coated reinforcement is used the most (19.69% in Rhode Island, 14.77% in the United

States) The remaining bridges in Rhode Island have galvanized reinforcing (2.07%), other deck protection (0.8%), or are defined as “not applicable” (16.84%)(FHWA 2018a). Items defined as “not applicable” refer to bridges without a deck (GPO 2004). After increasing the concrete cover, epoxy coated reinforcing bars are in general the second most common strategy for preventing reinforcement corrosion (McDonald 2009).

Different cyclical preservation strategies for bridge decks are (FHWA 2018d):

- Cleaning/washing bridge
- Flush drain
- Clean joints
- Deck/parapet/rail sealing and crack sealing

If it comes to condition-based maintenance the following strategies are used (FHWA 2018d):

- Repair/Replacement of Drains
- Joint seal replacement
- Joint repair/replace/elimination
- Electromechanical extraction (ECE)/Cathodic protection (CP)
- Concrete deck repair in conjunction with overlays, CP systems or ECE treatments
- Deck overlays

The latter, as an important part of bridge deck preservation is described in more detail hereinafter.

Table 3: Examples of cyclical agency rule (FHWA 2018d)

NBI Item 58	Preservation Activity	Interval Years
≥7	Deck Sweeping/Washing	1 to 2
	Crack Sealing	3 to 5
	Deck Sealing	3 to 5
	Polymer Overlay	8 to 12
	Polymer-Modified Asphalt Overlay	12 to 15

Table 3 shows typical interval years for preservation activities for NBI item 58 (deck). For example, a deck sweeping/washing could be done every 1 to 2 years and crack sealing every 3 to 5 years (FHWA 2018d). Further intervals for preservation activities of deck, superstructure and substructure by WisDOT (2016) can be found in Appendix 1.

Surface treatment

A prominent preservation strategy for bridge decks is the treatment of the wearing surface. Due to 76.68% of the Rhode Island bridge decks are made out of concrete (Graph 11 in Chapter 6.1.3) and 68.91% of the wearing surfaces are with Bituminous material (Graph 15 in Chapter 6.1.3), this study focuses on this materials.

To increase the durability of concrete, for example the water permeability and chloride penetration has to be reduced. Some of the deck coating strategies are alkyl alkoxy silane (AAS) (Liu 2017), polymer coating (Shi et al. 2012), mortar coating (Sanjuán and del Olmo 2001), calcium-silicate (Moon et al. 2007), and the injection of resin (Frangopol and Liu 2007).

The latter of the examples injects epoxy resin into cracks in the concrete and seals them. This procedure is cheap and reduces the corrosion of reinforcement because it is not exposed to air (Frangopol and Liu 2007).

AAS is a water emulsion coating that have no organic solvents (Liu 2017). Considering that organic coatings are generating air pollutants when manufactured and applied, silane treatment as inorganic coating could be an alternative (Liu and Vipulanandan 2001). It was found that concrete coated with AAS is more resistant to water absorption, carbonation, and chloride penetration, than a concrete with a acrylic coating (Liu 2017). However, silane treatments does not delay deterioration or improves the performance of a bridge and costs more than replacing the bridge joints (Frangopol and Liu 2007).

As guidance when certain coatings or different actions are appropriate, Table 3 shows the agency rules with its proposed interval years (FHWA 2018d). A polymer coating, which should be applied every 8 to 12 years, on the other hand, can reduce the mortar shrinkage and increase the mortar flexural and compressive strength on the surface of concrete. Also, the carbonation depth, chloride ion diffusion rate, and water absorption can be decreased with a polymer coating (Shi et al. 2012).

Additionally, mortar coatings are mainly used to protect the concrete against carbonation, which occurs due to CO_2 concentrations and humidity. Therefore, industrial mortar coating shows excellent performance measures in case of carbon dioxide barrier (Sanjuán and del Olmo 2001).

Furthermore, calcium-silicate coatings are found to be effective against chloride ion penetrations, because of the hydration of calcium-silicate, which then generates insoluble silicate compounds. Calcium-silicate coatings are also delaying the carbonation process and are more resistant to freezing and thawing (Moon et al. 2007).

Bituminous surface treatments

Pavement preservation in Rhode Island consists of crack sealing, micro-surfacing, asphalt rubber chip sealing (ARCS), paver-placed surface treatment (PPST), paver-placed elastomeric surface treatment (PPEST) thin overlay, whitetopping (RIDOT 2014b).

Sealing of cracks can either be done by blow clean, heat crack and then fill and overband, or by grinding out and heat crack and then fill with rubberized asphalt. Micro-surfacing on the other hand does not need much surface preparation and consist of polymer modified asphalt slurry (Emulsion, aggregate and Portland cement). ARCS consists of 20% crumb rubber and asphalt, which is then hot sprayed and afterwards covered with precoated stone and finished with rolling. This kind of treatment is easy and fast to apply and ideal for cold wet climates. Furthermore, PPST is a polymer emulsion, which is sprayed before the hot mix overlay and followed by rolling. This kind of treatment is efficient and used on roads with sound foundation. However, PPEST is a mixture of coarse-graded crushed aggregate and chemically modified crumb rubber asphalt binder. This kind of treatment is produced in a hot mix plant and applied with a one-inch thickness. Stress absorbing membrane interlayers (SAMI) is a special treatment and combines ARCS and PPEST. Whitetopping is a thin concrete overlay over existing asphalt and is useful for areas with traffic by heavy vehicles (RIDOT 2014b).

Additional bridge deck protections

Other possibilities to preserve a bridge deck are attaching steel plates, replacing expansion joints, and cathodic protection. The former instantly improves the structural reliability of the bridge. However, attaching steel plates is just preserving the bridge for a short period of time and cannot be seen as long-term solution. The replacement of expansion joints is one of the most cost effective strategy, but more replacement than preservation, because it does not delay deterioration or improves the performance. Cathodic protection, on the other hand, replaces anodes and therefore, prevents corrosion for a long time period. If replacing the bridge slab is considered a preservation strategy, this would be the most efficient, but also the most expensive preservation strategy (Frangopol and Liu 2007).

A different problem with bridge deck preservation is the halo effect. It can be described as corrosion which occurs due to chloride and moisture in the concrete. After a delaminated part of the bridge deck is replaced, it can be examined that the surrounding remaining concrete deteriorates faster (FHWA 2018d).

3.5.2. Superstructure

The superstructure as support of the deck and connection between substructure components has the following cyclical preservation activities (FHWA 2018d):

- Clean/wash bridge
- Seal concrete

On the other hand, condition-based maintenance activities are (FHWA 2018d):

- Seal/patch/repair superstructure concrete
- Protective coat concrete/steel elements
- Spot/zone/full painting steel elements
- Steel member repair
- Fatigue crack mitigation (pin-and-hanger replacement, retrofit fracture critical member
- Bearing restoration (cleaning, lubrication, resetting, replacement)
- Movable bridge machinery cleaning/lubrication/repair

Bridge washing

Cleaning and washing the bridge is one of the cyclical strategies also used by RIDOT (RIDOT personnel 2018). Since 1999, over a span of 4 years, a large number of bridges were washed by RIDOT and inspection result documented in a study. This study found structural benefits, such as extended bridge and paint life, mainly due to cleaning of deicing salts and debris from the bridge surface. Every bridge which was washed twice a year showed no difference in condition state after an 8-year period. Therefore, the study recommended bridge washing for the best 2 condition states out of 5 in total, which relates to NBI condition ratings 6 to 9 (RIDOT 2002). However, to wash a bridge certain materials cannot be washed into waterways and thus need to be collected prior to washing. This makes bridge washing expensive and labor intensive, if bridge washing is not applied frequently. Nonetheless, bridge washing for steel bridges is found to be beneficial, if the effect on paint condition exceeds the cost for bridge washing (Berman, Jeffrey et al. 2013). Additionally, bridge washing contributes the movability of bridge joints and bearings, which prevents damage to the elements themselves or other bridge parts, for example due to freezing and thawing. Therefore, it is recommended that bridges are washed every spring to runoff the salt deposits and winter weather results, as well as considering the environmentally impact of bridge washing and considering the related costs (Burgdorfer, Ryan et al. 2013).

Painting steel

Another preservation strategy used by RIDOT is painting bridges (RIDOT personnel 2018). If preserving steel painting, it can be done in three ways: spot, zone or full repainting. If a small section of the bridge surface is delaminated or rusted, this spot is painted. This kind of repair can only be applied if the corrosion is limited and the remaining coating is in good condition. The difficulty with spot painting is not to damage the remaining coating while repairing the damaged area and ensuring that there is no transition zone between the new painting and old painting. Zone painting is applied if a larger area has deteriorated and needs new coating. The restrictions and difficulties are similar to spot painting. Complete repainting is done if the coating has deteriorated completely and the system needs to be cleaned before the new coating can be applied. In order to make the best economically decision which painting strategy is the most cost effective, bridge data needs to be analyzed. However, it was found that either a complete repainting at condition state 4 or cyclical spot or zone painting could be applied (Agbelie et al. 2018).

3.5.3. Substructure

The substructure supports the superstructure and distributes all the loads into the bridge supports. To preserver substructure the following cyclical actions could be used (FHWA 2018d):

- Clean/wash bridge
- Seal concrete

For condition-based preservation activities there are (FHWA 2018d):

- Patch/repair substructure concrete
- Protective coat/concrete/steel substructure
- ECE/CP
- Spot/zone/full painting steel substructure
- Pile preservation (jackets/wraps/CP)
- Channel cleaning/debris removal
- Scour countermeasure (installation/repair)

Preservation strategies for substructures are similar to preservation strategies of superstructures, with the difference of channels, piles, and scour.

Scour preservation

The substructures of bridges going over waterways is vulnerable to scour. The type of service under 368 bridges in Rhode Island is a waterway or a waterway and a different type of service. Of these bridges over a waterway 102 bridges need an underwater inspection (FHWA 2018a).

To prevent scour, bridge foundations are designed for potential scour by designing the bridge without any streambed material in the scour are to support the foundation. For existing scour critical bridges, a scour countermeasure is recommended. In this case the importance of the bridge, the risk and the urgency are determining the actions taken. For critical bridges hydraulic, structural, or biotechnical countermeasures can be installed (FHWA 2009).

3.5.4. RIDOT´s preservation strategies and actions

Considering a report published by the RIDOT in 2014 major rehabilitation or replacement is done for poor bridges (Rating 1-4 in the FHWA bridge rating scale, shown in Table 1), preservation like repainting and minor repairs for fair bridges (Rating 5-6 in the FHWA bridge rating scale), and low maintenance like sweeping and washing for good bridges (Rating 7+ in the FHWA bridge rating scale), as shown in **Fehler! Verweisquelle konnte nicht gefunden werden.** (RIDOT 2014a).

Figure 6: Bridge ratings and condition of Rhode Island bridges (RIDOT 2014a)

Concerning preservation strategies, the RIDOT uses bridge washing, replacing joints, painting, eliminating design flaws, sealing concrete decks/abutments, and plating steel (RIDOT personnel 2018). Other strategies are deck repairs, minimum to moderate concrete or steel superstructure repairs, moderate substructure repairs, and culvert repairs (Rhode Island Statewide Planning Program 2018). The decision on which strategy is applied for a bridge at which time, similar to Figure 6, is done by the bridge management system used by the RIDOT, AASHTOWare Bridge Management, or as mentioned in Chapter 3.2.8 on basis of their asset management (RIDOT personnel 2018). The program AASHTOWare Bridge Management is described hereinafter.

3.5.5. AASHTOWare Bridge Management

The software used by RIDOT is created by AASHTO and is called AASHTOWare Bridge Management (BrM). Due to no access and no analysis run or data used in this study, AASHTOWare BrM is just briefly described hereinafter.

This program uses inspection data as foundation to model structures, deterioration, funding and projects to help with the decision process. Figure 7 gives an overview about the different components of AASHTOWare BrM. Element-level inspection is used to make decision, have detailed cost data and element deterioration. For elements there are 4 condition states (1 Good, 2 Fair, 3 Deteriorated, 4 Poor). It can also be validated with NBI ratings. Included in inspection data is risk assessment (AASHTO 2016).

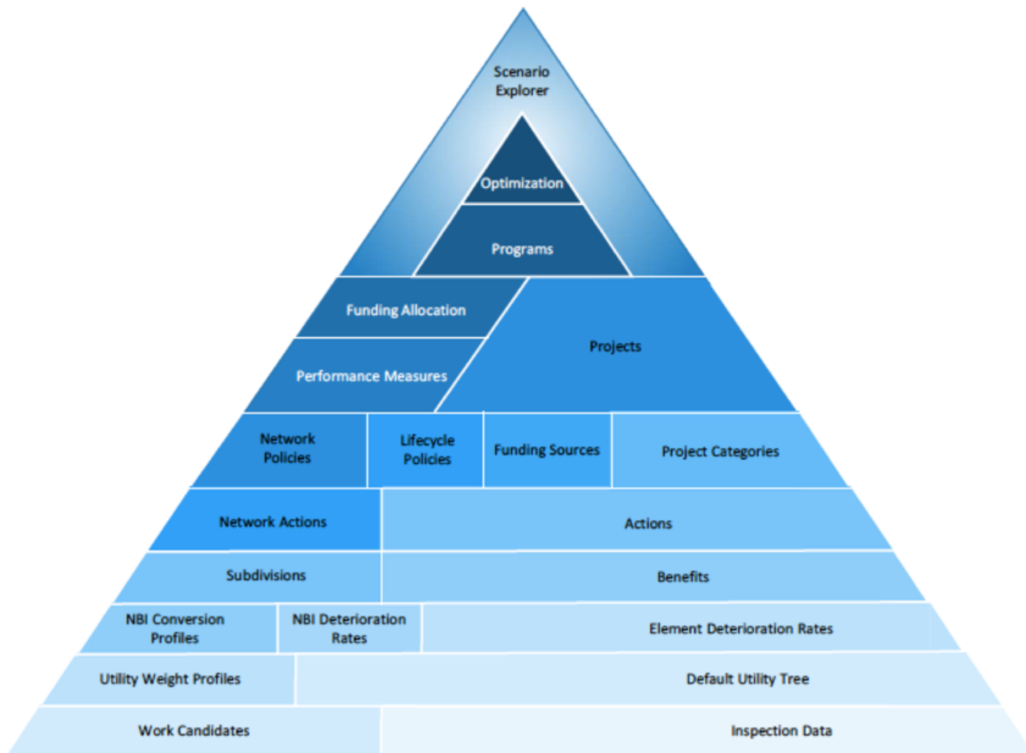


Figure 7: Optimization Pyramid of AASHTOWare (AASHTO 2016)

The category default utility tree is the base for cost and deterioration models. Through repairs the utility value of a bridge should improve. The utility value consists of condition, lifecycle, mobility, and risk. Each branch of the tree has a weight which can be defined for each project. Starting with value at the end of the branches the total utility value is calculated with its base and scale values, as well as their weight. For preservation work, life-cycle is the most important branch, because preservation does not significantly improve the condition and the benefit of doing the work now instead of later is recorded in this branch. Risk is associated with hazards, among others. Mobility is considered the ability to keep the bridge in a condition in which it remains usable (AASHTO 2016).

Deterioration models are based on the elements rated with the 4 condition states (good, fair, poor, severe). Each element is modeled individually by the program. As only input, the median years for each condition state can be changed according to the regional area. For the NBI rating, the deterioration is applied by using a time period in which a bridge stays in a condition state, or by NBI conversion profiles. These profiles are converting the element-level conditions to a NBI rating (AASHTO 2016).

In the benefits screen, the element condition can be changed by actions. Actions can be changed, removed, replaced elements, as well as creating protective systems. For every action a percentage of change from condition to another can be set. Also the risk can be reduced. The total and element costs for the action are set at the action screen, in which the benefits can be added. Additionally, the deferment interval can be set. In network policies the operator can choose which actions would be used as combinations and what work has to be done in these actions. For example, the deck would not be preserved if the superstructure will be replaced. With AASHTOWare BrM it is also possible to add funding sources, run life-cycle cost analysis, and show project analysis results and future needs. Furthermore, a program can connect all the information set before. The optimization button then runs the program and gives recommendations, and program results, among other data. Finally, the scenario explorer can run optimizations several times and compares the results(AASHTO 2016).

4. COST

Beginning with the MAP-21 and the FAST Act bridge preservation is now eligible for federal funding. Routine maintenance, however, is not eligible for federal funding (FHWA 2018d). Considering that financial support is one of the most important aspects of commitment to a strategy, bridge preservation activities are becoming more common.

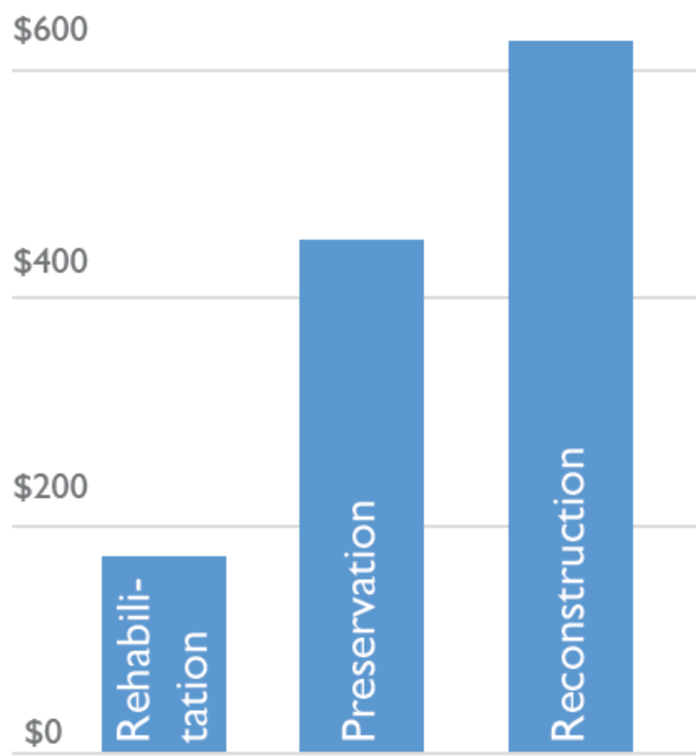


Figure 8: Bridge Repair Costs per Square Foot (Rhode Island Statewide Planning Program 2018)

This follows from the fact that bridge preservation on the one hand cost more per square foot than rehabilitation, however, on the other hand cost less than reconstruction. According to Figure 9, rehabilitation in Rhode Island cost slightly below \$200/ft^2, \$175/ft^2 is assumed, and preservation slightly above \$400/ft^2, \$425/ft^2 is assumed (Rhode Island Statewide Planning Program 2018). Rehabilitation is defined as major work required to restore the structural integrity of a bridge and to correct major safety defects (FHWA 2018d). Reconstruction of a bridge is slightly above \$600/ft^2, \$625/ft^2 is assumed. If a bridge becomes structurally deficient it must undergo major rehabilitation or replacement. The cost associated with this are 3 to 4 times higher than preserving the bridge (Rhode Island Statewide Planning Program 2018). Therefore, this chapter gives a brief overview on sources of monetary funds (Chapter 4.1) and what expenditures Rhode Island has (Chapter 4.2)

4.1. Funding

Additionally, the State of Rhode Island Transportation Improvement Program (STIP) uses federal funding through the Fixing America´s Surface Transportation (FAST) Act. The FAST Act is a five-year program passed by the Congress in December 2015, which continues the MAP-21 focus on performance management and measurement, as well as asset management. It is expected that the FHWA will provide around \$1.08 billion in funding to Rhode Island from the federal fiscal year (FFY) 2018 to 2021 and that the FAST Act will provide Rhode Island an average of \$271 million annually (Rhode Island Statewide Planning Program 2018).

With this funding and other monetary sources Rhode Island, in the form of RIDOT, signed RhodeWorks into law, a 10-year, \$4.7 billion investment program to bring the high number of deficient bridges in a state of good repair. Recently there was no state-funded capital program and only the state´s gas taxes supported a limited maintenance program (RIDOT 2014a). The gas tax was $0.34 per gallon in FFY 2017 and is scheduled to increase to $0.38 per gallon in 2027. The recipient with the highest share is the RIDOT with $0.1825 per gallon, as shown in Figure 9 (Rhode Island Statewide Planning Program 2018).

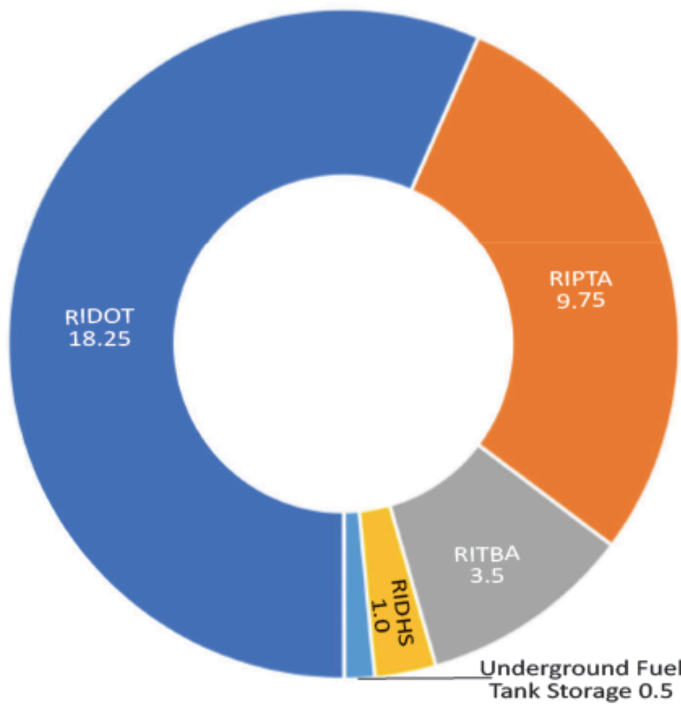


Figure 9: Rhode Island Gas Tax Recipients 2017 (Rhode Island Statewide Planning Program 2018)

The remaining monetary funds needed are planned to be achieved by a truck-only tolling system (RI.gov 2018), Transportation Investment Generating Economic Recovery (TIGER) grants (Cicilline, David 2018), the Strengthen and Fortify Existing (SAFE) Bridge Act (Langevin, Jim 2017), and more. The tolling system will collect approximately 10% of the $4.7 billion ten-year budget of RhodeWorks and will be collected at twelve locations on six major highway corridors. Each tolling station is assigned to one or more bridges which will be replaced or repaired with this revenue. The toll will be ranging from $2 to $9 and the median cost will be $3.5 (RIDOT 2018a). The STIP expect a toll revenue of $21.7 million annually and costs of $2.4 million for the toll collection (Rhode Island Statewide Planning Program 2018). TIGER grants are bringing $20 million to repair and improve the bridges and roads of Route 37 between Cranston and Warwick (Cicilline, David 2018), whereas the SAFE act bill would deliver $170 million to repair Rhode Island deficient bridges (Langevin, Jim 2017). Additionally, the National Highway Performance Program (NHPP) is funding the state Planning and Research (SPR) which expenditures must support improving condition, safety, and mobility of non-NHS highway bridges that are on a federal-aid eligible highway, among others. However, bridge preservation routine operations are typically funded with state funds (Rhode Island Statewide Planning Program 2018).

4.2. Expenditures

The monetary funding is then to be used for road and bridge construction projects ($200 million), reconstruction of the 6-10 interchange ($400 million), investment in the Providence Intermodal Transit Center ($100 million), a new Pawtucket-Central Falls Train Station ($40 million), design-build contracts for interstate bridges ($38 million), the truck-tolling system ($34 million), and a new Southern Rhode Island Travel Plaza and Transit Hub ($12 million). Rhode Island has spent $824 million of its funding the FY 2017. In the 2016 FFY already $174 million were out for bid for construction, leaving Rhode Island with a total of $898 million in the first year of RhodeWorks (RI.gov 2018).

Rhode Island has planned to fix more than 150 structurally deficient bridges and preserve 500 bridges through repairs from becoming deficient (RI.gov 2018).

5. Methodology

The analysis of this study is based on NBI data published by the FHWA. The NBI data is provided in coded text files. Data is available for every state between 1992 and 2017. Beginning with the MAP-21 Act, every state needs to collect and submit element-level data for all NHS bridges, starting with element-level inspection in 2014 and submitting in 2015 (Campbell et al. 2016). NBI element data is also publishes by the FHWA and provided as coded xml files. This study focuses on NBI data and NBI element data of Rhode Island.

In Chapter 5.1, the first step of processing the data is described. The data is imported, sorted and prepared for the analysis. Afterwards, Chapter 5.2 outlines how the data was analyzed and what performance measures can be generated.

5.1. Data processing

After downloading all bridge records for Rhode Island, the delimited files were imported into excel. The imported NBI data contains structure numbers, condition states (deck, superstructure, substructure, channel, culvert), bridge deck areas, state codes, and locations codes, among several other data. Included in the NBI data are all bridges with a span of 20 feet or more (GPO 2004). To decode the NBI data the *Recording and Coding Guide for Structure Inventory and Appraisal of the Nation´s Bridges* is needed (FHWA 1995b).

The NBI element data includes structure numbers, element numbers, element parent numbers, and condition states for every element. Different to the condition states of the NBI data, which has a 9-point scale, there are 4 condition states for the

NBI element data (CS1: good, CS2: fair, CS3: poor, CS4: severe). To decode the NBI element data the *Specification for the National Bridge Inventory Bridge Elements* is needed (FHWA 2014).

After decoding the data, an in-depth analysis of the NBI data of RI is run. Several studies concentrated focus on bridges in the United states as a whole country, not on single states (Lee, Seung-Kyoung 2012a p. 1)(Andrade and Comité euro-international du béton 1995)(Wu, Nien-Chun 2010). Approaches using geographic information systems and a computing application (Wu, Nien-Chun 2010), regression models which linked environmental variables to predict condition ratings of bridges (Andrade and Comité euro-international du béton 1995), and determining cause of deterioration in bridges (Lee, Seung-Kyoung 2012a). This study gives an overview on the bridge condition in the United States (Chapter 6.1.1) and focuses on their comparison with bridge data of RI (Chapter 6.1.2 to Chapter 6.1.13); for example, condition in different Rhode Island counties (Chapter 6.1.2), bridge ages in RI (Chapter 6.1.10), and future condition ratings (Chapter 6.1.12).

The program R is used as supporting tool to create maps and further analyze the given data.

5.2. Developing performance measures

In a similar study by G. Hearn for all states of the United States (Hearn 2017), performance measures for bridge preservation were developed. In other studies, performance measures were used to characterize the behavior of in-service bridge superstructures (Gheitasi and Harris 2014), and probabilistic approaches to assist the bridge management process (Biondini et al. 2014)(Saeed et al. 2017). Also, uncertainties were added to no maintenance deterioration and under maintenance deterioration processes and bridge performances (Liu and Frangopol 2004).

NBI data was used in recent studies to estimate the future condition of highway bridge components in Illinois (Bolukbasi et al. 2004), estimating inspection intervals for bridges with superstructure components (Nasrollahi and Washer 2015), optimizing and standardization the bridge design decision and thus reducing maintenance cost (Jootoo and Lattanzi 2017), and finding inconsistency in the NBI database (Din and Tang 2016).

However, this study focusses on the authoring of performance measures for bridge preservation in Rhode Island. Performance measures are based on National Bridge Elements (NBEs) and Bridge Management Elements (BMEs) defined by the AASHTO *Bridge Element Inspection Guide Manual* (MBEI)(AASHTO 2010).

NBEs are defined as primary structural components, such as:

- Deck
- Superstructure
- Substructure
- Culverts
- Bridge rails
- Bearings

These elements are necessary for the safety of the primary load carrying members and the overall condition determination (AASHTO 2010). Most of these NBEs will need rehabilitation in their life-cycle, but could also be preserved instead of rehabilitated (Hearn 2017).

BMEs, on the other hand, are defined as bridge elements, such as (AASHTO 2010):

- Joints
- Wearing surfaces
- Protective coatings

BMEs are likely to be replaced or renewed as part of the preservation process. Therefore, NBEs are the elements to preserve and BMEs are the elements which have the cause of preserving the NBEs (Hearn 2017). Therefore, NBI data and NBI element data are examined simultaneously. For a holistic analysis both datasets, stored in separate files, are merged into one file with the program R.

After that, the element ratings are used to develop performance measures. Based on the 9-point rating scale used for NBI data and the *National Performance Management Measures for Assessing Bridge Condition (NPMM)* (23 CFR 490.411) (U.S. Department of Transportation 2017), a bridge is in poor condition if one of its NBI items, 58 –Deck, 59 – Superstructure, 60 – Substructure, or 62 – Culvert is 4 or less. A bridge is in good condition if the lowest rating of the 4 NBI items (58, 59, 60, 62) is 7 or more. A fair condition is measured by NBI items having a lowest rating of 5 or 6 (U.S. Department of Transportation 2017).

In a previous study by Hearn (2017), the ratings are used to developed performance measures by putting bridge elements in relationships with four possible outcomes, as shown in Table 4.

Table 4: Outcomes of element relationships (Hearn 2017)

NBE	Good/Fair BME	Poor BME
Good/Fair	Good preservation	At risk
Poor	Poor condition	Poor condition

For this study, a NBE is in good condition, if the elements are in good or fair condition. A NBE is in poor condition, if the NBEs are in poor condition (Hearn 2017). BME´s are in poor condition if the sum of condition states 3 and 4, of the 4-point scale of NBI element data condition rating, exceeds the amount of 10% of the total quantity, defined by the AASHTO *commonly recognized (CoRe) set of bridge elements* (AASHTO 1998).

If NBE elements are in good condition and BME elements are in good condition, the bridge has a good preservation state. If the BME elements are in poor condition, while the NBE elements are in good condition, the bridge is at risk to deteriorate in poor condition. NBE elements in poor condition are mostly candidates for rehabilitation and replacement, not for preservation. Therefore, all bridges with NBE elements in poor condition, are overall in poor condition, because preservation or repairs of BMEs will not restore the NBE (Hearn 2017).

According to the AASHTO MBEI the elements are grouped not only by NBE or BME, also by major assembly (deck, superstructure, substructure, or culvert) and by material (reinforced concrete, prestressed concrete, steel, or timber) (AASHTO 2010).

Additionally, this study is using element types as groups to analyze bridge performance, based on (Hearn 2017). The data used in the study by G. Hearn, however, is unfiltered NBI and NBI element data.

The datasets in this study are filtered by bridges constructed, reconstructed, or improved within the last ten years. Since these bridges may be in good condition as a result of preservation, but more likely because of the young age or rehabilitation and replacement were done. The filtering process was done by applying the same rating as for the performance measures, and by using the NBI items "27 – Year built", "97 – Year of improvement", and "106 – Year reconstructed". Afterwards, the numbers gained are subtracted from the initial performance measure numbers.

The performance measures created by relationships between elements, and filtered to ensure better results, to analyze the need of preservation and bridges in good condition can be seen in Table 5.

Table 5: Elements relationships (Hearn 2017)

Preservation Elements	Exposure Elements
NBE	BME
NBE deck	BME
NBE superstructure	BME
NBE substructure	BME
NBE culvert	BME
NBE concrete	BME
NBE prestressed concrete	BME
NBE steel	BME
NBE timber	BME
NBE aluminum, wrought iron, cast	BME
NBE concrete	BME coating
NBE steel	BME coating
NBE deck	BME wearing surfaces
NBE	BME joint
NBE deck	BME joint
NBE superstructure	BME joint
NBE substructure	BME joint
NBE concrete	BME joint
NBE prestressed concrete	BME joint
NBE steel	BME joint
NBE timber	BME joint
NBE	BME joint, open
NBE	BME joint, other
NBE	BME joint, assembly without seal
NBE	BME joint, assembly with seal
NBE	BME joint, compression
NBE	BME joint, strip seal
NBE	BME joint, pourable

At first all NBE elements (deck, superstructure, substructure, and culverts), as elements to preserve, are analyzed in relationship with all BME elements (joints, coatings, wearing surfaces). Followed by each NBE elements analyzed one by one with all BME elements, before every NBE element material is put in relationship with all BME elements. The NBE materials concrete and steel are then compared with their relating BME coating and the NBE deck with the BME wearing surfaces. The same procedure of NBE elements and NBE materials is done for BME joints, and afterwards every joint type is put in relationship to all NBE elements. If all NBE elements are used in relationship to BME elements, the NBI item CAT 23 – Overall condition, is used (U.S. Department of Transportation 2017).

5.3. Applying performance measures

The created performance measures are used to calculate the preservation needs, based on (Hearn et al. 2013). Therefore, the bridges at-risk are listed by count and bridge area, and divided by the service interval needed to keep the bridge in fair or good condition or the number of years planned for preventive maintenance. These numbers are obtained by Chapter 3.5.1 and Appendices 1 to 3. The preservation needs are calculated as followed:

$$(1) \qquad Preservation\ need = \frac{Preservation\ candidates}{Service\ interval}$$

If the median number of years a bridge remains in the condition states 9 to 5 are known, this number can be used to determine the preservation need for all preservation candidates (Hearn et al. 2013).

The preservation need as a result of Equation 1 determines the annual need for work. The preservation costs resulting from the annual need for work are calculated as follows:

$$(2) \qquad Preservation\ cost = Preservation\ need\ x\ Average\ cost$$

The preservation cost quantifies the resources needed for the preservation needs (Hearn et al. 2013). The average costs are obtained by Chapter 4 and measured in square feet. Therefore, the preservation needs are also obtained in square feet by Equation 1.

The advantage of preservation can be computed by calculating Equations 1 and 2 with data related replacement. The results can then be compared by using Equation 3:

$$(3) \qquad Preservation\ advantage = Replacement\ cost - Preservation\ cost$$

The difference between replacement costs and preservation costs eventually shows the monetary preservation advantage.

Another study by (Hearn 2015) proposes Equation 4 to quantify the yearly program funding for bridge preservation and simultaneously display the effect of annual funding.

$$(4) \qquad Q_e = \frac{F}{U_e} \frac{(1-T_f)^N - 1}{(-T_f(1-T_f)^N)}$$

This equation calculates the repair of a quantity of BMEs (Q_e), where U_e is the unit cost of repairs to BMEs, T_f the annual probability of transition of a NBE to poor condition, N the number of years the program will run, and F the amount of annual funding.

To get the number of years the program has to run until no candidate remains, Equation 4 has to be transposed.

$$(5) \qquad N = \frac{\ln \frac{F}{F+Q_e T_f U_e}}{\ln 1 - T_f}$$

In equation 5 the annual transition probability for deterioration is needed to calculate the number of years in which the program will be completed. Transition probabilities differ between elements and actions taken. Table 6 shows examples for transition probabilities.

Table 6: Transition probabilities example (Golabi and Shepard 1997)

Condition state	Optimal action	Unit cost	Transition probabilities			
			1	2	3	4
1	Do nothing	0	0.95	0.05		
2	Seal cracks . . .	2	0.47	0.49	0.04	
3	Clean, reinforce	6	0.18	0.48	0.31	0.03
4	Rehab unit	50	0.39	0.39	0.16	0.06

For this study a transition probability of 0.02 is used based on (Hearn 2015). The number of BMEs that needs to be repaired is shown in Equation 6 (Hearn 2015).

$$(6) \qquad Q_e = NR_e + D_e$$

The preservation needs calculated in equation 2 are defined as $R_{e,}$ or can be calculated by Equation 7.

$$(7) \qquad R_e = \frac{F}{U_e}$$

The annual funding divided by the average cost of preserving an element equals the amount of yearly preservation needs which can be executed with the amount of annual funding provided.

Equation 6 can also be transposed to Equation 8 to find the deck area deteriorating to poor condition.

$$(8) \qquad D_e = Q_e - NR_e$$

With all this information an in-depth analysis of the preservation program can be made.

6. Results

This chapter seeks to present and discuss the results, applying the methods described. Chapter 6.1 will display the current state of Rhode Island bridges by processing the NBI data; with subsections for the different kinds of observations. In Chapter 6.2 the results of developing and applying the performance measures are shown by using NBI data, as well as NBI element data. The subsections are evaluating the overall preservation performance and an in-depth analysis of the preservation program in Rhode Island.

6.1. Current state of Rhode Island bridges

The goal of every state is to reach a condition state of 90% of sufficient bridges, or - put another way- under 10% of deficient bridges. Figure 10 shows how Rhode Island wants to reach this goal over the years.

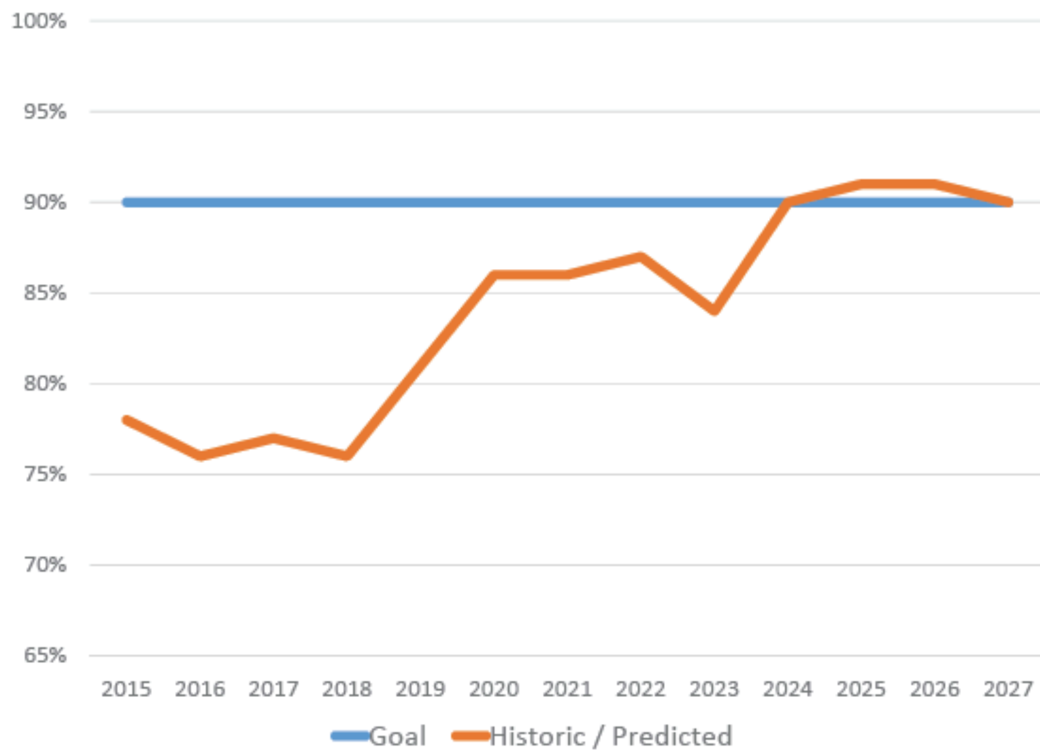


Figure 10: Rhode Island Bridge Deck Area Condition Trend (Rhode Island Statewide Planning Program 2018)

The figure forecasts a decrease in sufficient bridges in 2018, but a steep incline over the years 2019 and 2020, because of further actions described in the Chapters 1 and 4.1. After year of small changes and a small decrease in 2023, the goal will be reached by the year 2024. For the year 2018 a percentage between 75% and 80%, close to 76%, is predicted. The results described hereinafter show the current state of Rhode Island´s bridges.

6.1.1. Bridge condition in the United States

However, not only Rhode Island faces problems with bridges. The nations infrastructure has a D+ grade in the 2017 Report Card for Americas Infrastructure of the American Society for Civil Engineers (ASCE). Slightly better but not encouraging is a C+ for the nations bridges (ASCE 2017). The latest data from the NBI indicates that there are 615,002 Bridges in the United States of which 54,560 are structurally deficient. That is 8.9% in 2017 compared to 11.5% in 2010. The decrease shows the progress that has been made to reduce the number of structurally deficient bridges (FHWA 2017b).

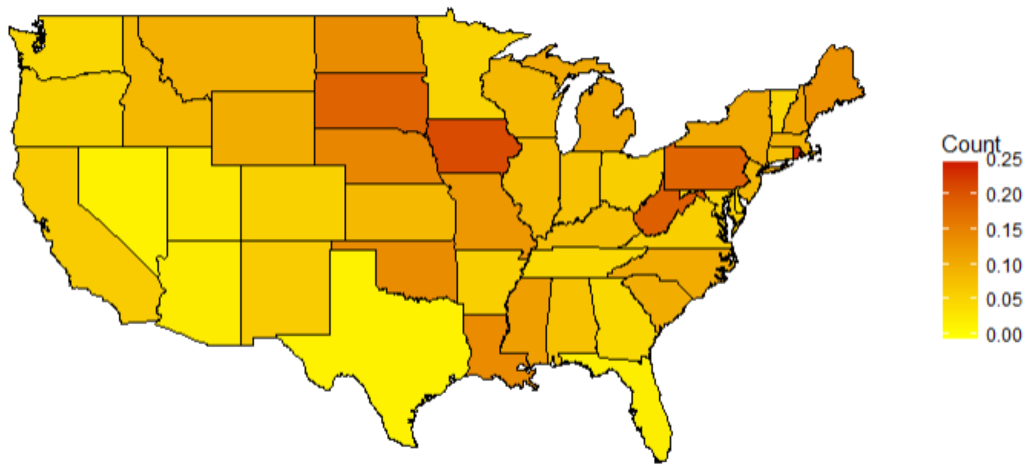


Figure 11: Structurally deficient bridges by bridge count (%) in every state in the United States (FHWA 2018a)

However, Figure 11 shows the percentage of structurally deficient bridges per state by bridge count. It is noticable that states in the northeast, especially Rhode Island, Pennsylvania, and West Virginia, as well as states in the Midwest, such as South Dakota and Iowa, have a higher amount of structurally deficient bridges (FHWA 2018a).

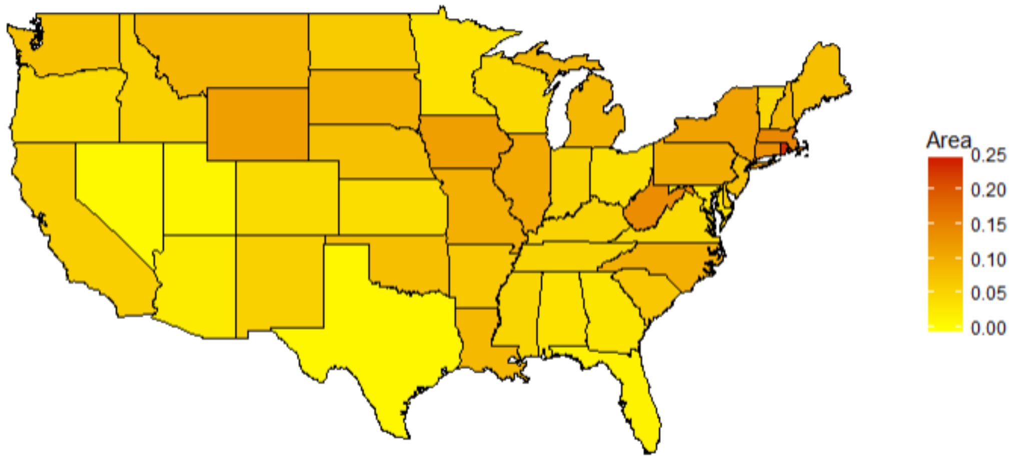


Figure 12: Structurally deficient bridges by bridge area (%) in every state in the United States (FHWA 2018a)

Figure 12 indicates the same dispersion, but shows that the difference in the area of structurally deficient bridges in these states and other states is not as high as in the bridge count in Figure 11, except in Rhode Island, which has a dark red in both figures that indicates a high percentage (FHWA 2018a).

Additionally, the average age of the nations bridges is 43 years and most of the bridges were designed for a lifespan of 50 years. Therefore, an amount of $123 billion would be required to rehabilitate all bridges in the United States (ASCE 2017). This amount increased from $9.4 billion in 2005 (Kim and Yoon 2010) over $76 billion in 2013 (Mondoro et al. 2017).

6.1.2. Bridges by county and condition

In Rhode Island, there are 5 counties and 778 bridges. The majority of bridges are in Providence County (around 60%, 473 bridges), which is also the largest county, followed by:

- Washington County (around 18%, 142 bridges)
- Kent County (around 15%, 115 bridges)
- Newport County (around 5%, 40 bridges)
- Bristol County (around 1%, 8 bridges)

Concerning the condition of the counties bridges, Figure 13 shows, Bristol County (37.5%) had the highest number of structurally deficient bridges in 2007 in case of bridge count, followed by Newport County (27.9%), Providence County (23.3%), Washington County (22.6%), and Kent County (17.6%) (FHWA 2018a).

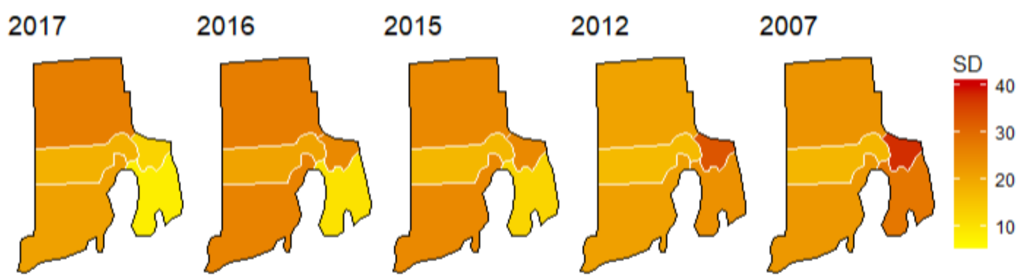
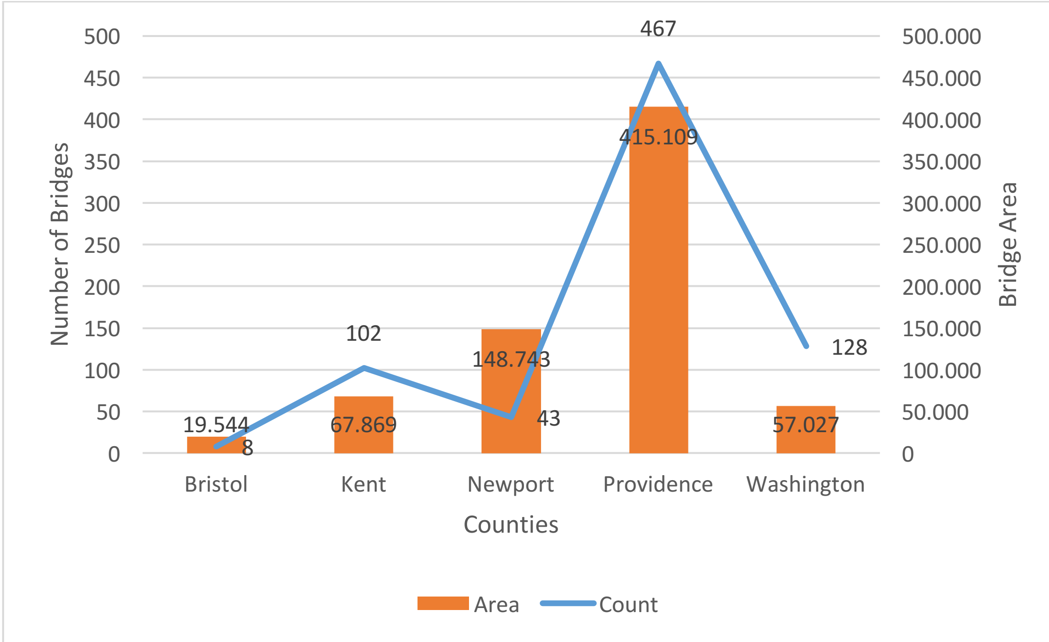


Figure 13: Structurally deficient bridges by count (%) in every county in Rhode Island (FHWA 2018a)

Graph 7 shows the number of bridges of each county, as well as the total area 10 years ago, in order to compare with todays data shown in Graph 8. The county with the highest amount of structurally deficient bridges has the fewest bridges and the smallest geographical area. Interesting is the Providence county with the third highest amount of structurally deficient bridges, but with by far the most bridges and highest bridge area in 2007 (FHWA 2018a).



Graph 7: Count and area of bridges in every county in Rhode Island in 2007 (FHWA 2018a)

According to the area, Figure 14 shows that Newport County has the highest amount of structurally deficient bridge area (52.26%) in 2007, followed by Providence County (31.1%), Kent County (21.84%), Washington County (19.43%), and Bristol County (13.73%). This can be explained because Newport county has the highest average area per bridge count (3,459 per bridge) and is the county with the second highest bridge area in 2007. Combining this with the second highest number of structurally deficient bridges in 2007, Newport County gets the biggest area of structurally deficient bridges (FHWA 2018a).

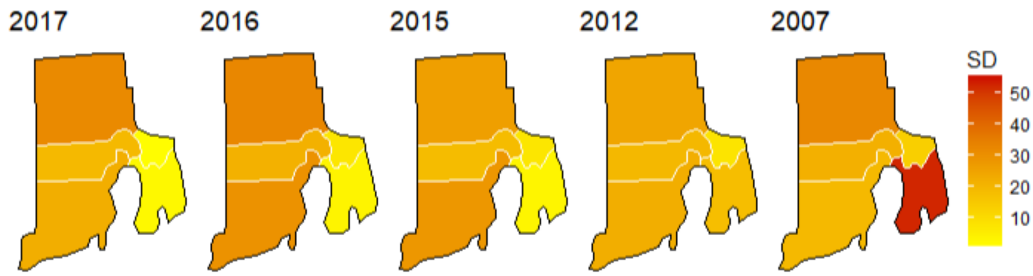
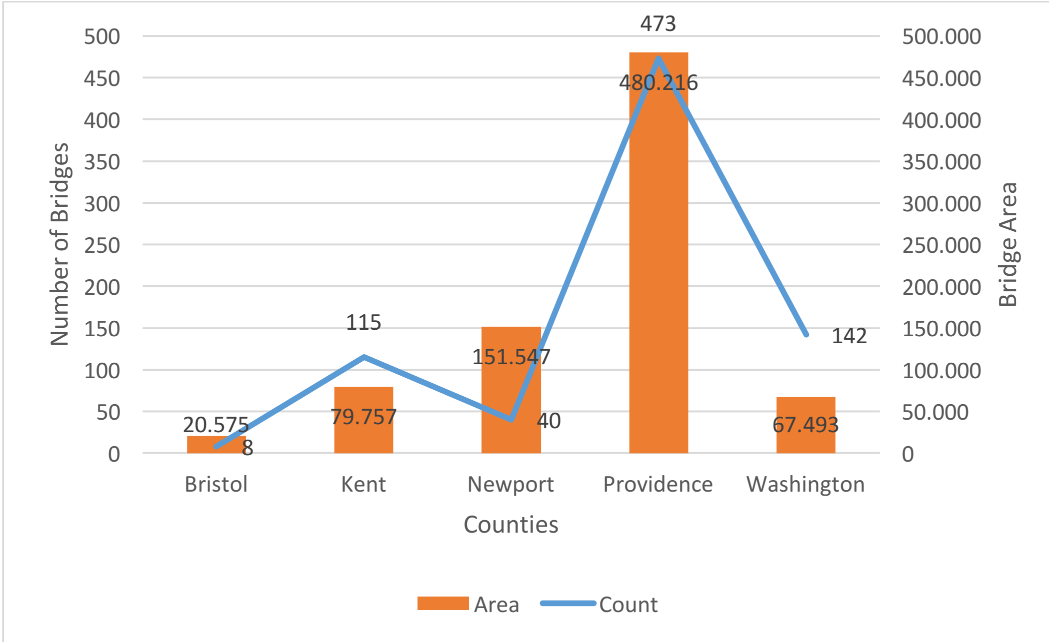


Figure 14: Structurally deficient bridges by area (%) in every county in Rhode Island (FHWA 2018a)

As Figure 13 and Figure 14 are showing, Bristol County and Newport County improved over the last ten years and are now the second last (Bristol County 12.5%) and last (Newport County 7.5%) in case of structurally deficient bridge count, shown in Graph 8. The same effect is shown regarding the area, where Newport County (2.97%) is second last and Bristol County (1.55%) is last in 2017. However, the condition of bridges became worse in the following counties starting with the worst condition: Providence County (Count 26.6%, Area 31.77%), Washington County (Count 21.1%, Area 22.41%), and Kent County (Count 18.3%, Area 19.43%) (FHWA 2018a).



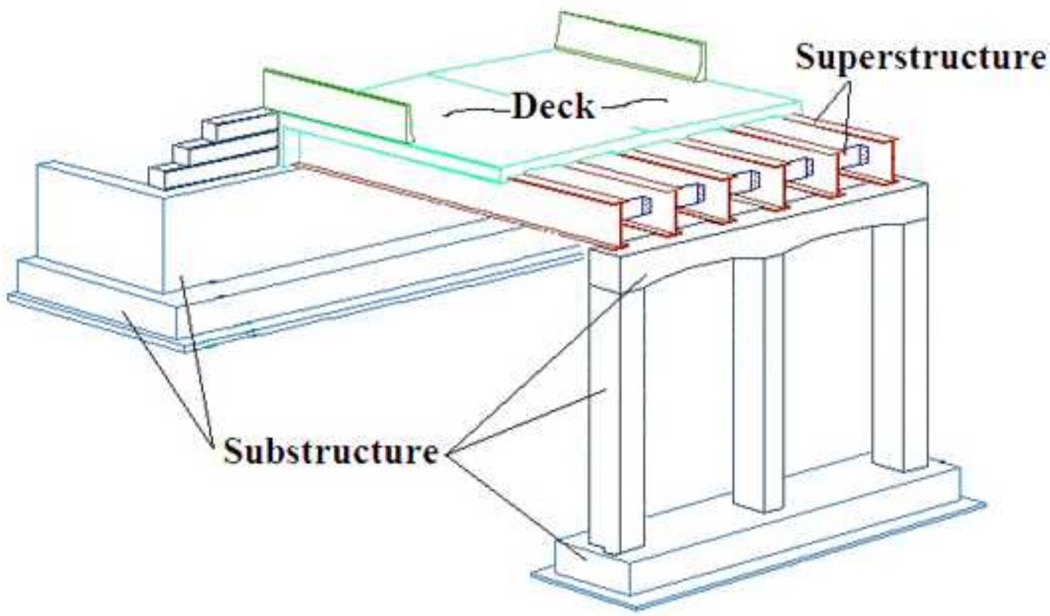
Graph 8: Count and area of bridges in every county in Rhode Island in 2017 (FHWA 2018a)

Bristol County improved through for example replacing the Barrington River Bridge with a new bridge in 2009, as well as rehabilitating the Warren River Bridge in 2009, which explains the different bridge area in 2017 (James Baughn 2018). Newport County replaced the 2,982.5 feet long Sakonnet River Bridge in 2012 and thus improved their structurally deficiency numbers (RITBA 2018).

After these counties improved the third highest in bridge count and second highest in bridge area, Providence County, becomes the first in both structurally deficient bridge counts and area. This is related to the increase in structurally deficient bridges (23.3% in 2007 to 26.6% in 2017) and just a slight decrease in structurally deficient bridge area (32.1% in 2007 to 31.77% in 2017) (FHWA 2018a).

6.1.3. Bridge types

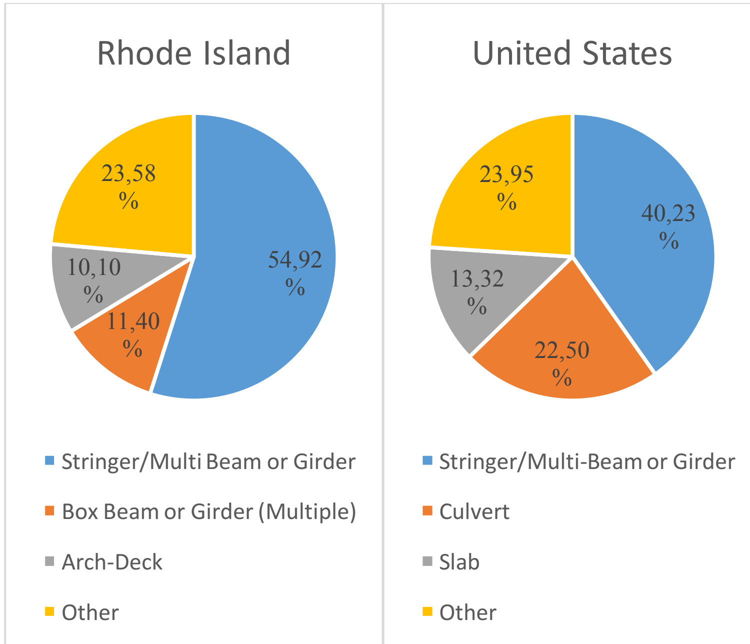
A bridge consists of various different parts, included in the three main bridge elements bridge deck, superstructure and substructure, as shown in Picture 11.



Picture 11: Structural elements of a typical highway bridge (MDOT 2018)

The deck is described as an element that carries the traffic, whereas the superstructure supports the deck and connects the substructure components. The substructure is defined as an element that supports the superstructure and distributes all loads to the bridge footings (MDOT 2018).

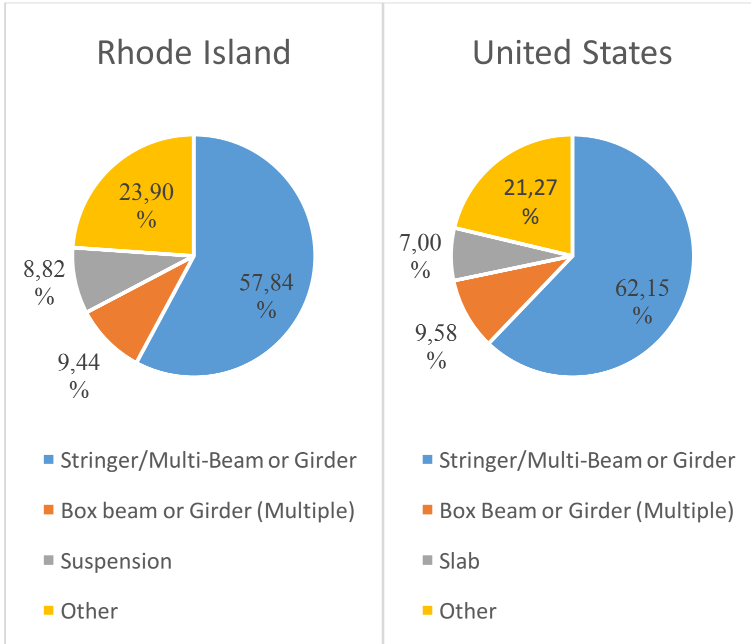
According to the NBI database most of the bridges in Rhode Island are stringer/multi-beam (Picture 12) or girder bridges (54.92%), followed by box beam or girders (Multiple) bridges (11.40%) and arch-deck bridges (10.10%), as shown in Graph 9. In the United States most of the bridges are also stringer/multi-beam or girder bridges (40.23%), but culvert bridges (22.50%) are the second and slab bridges (13.32%) the third most bridges in the country (FHWA 2018a).



Graph 9: Most used bridge types by bridge count (%) (FHWA 2018a)

Picture 12: Steel stringer/multi-beam bridge – Davidson County Bridge 89 on the Lexington Bypass (NCDOT 2013)

A similar distribution shows Graph 10 in case of most used types by bridge area.

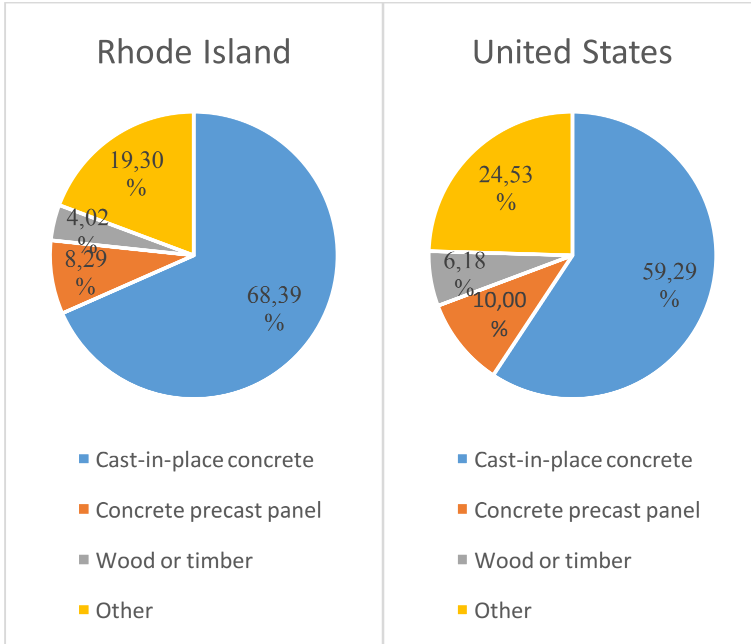


Graph 10: Most used bridge types by bridge area (%) (FHWA 2018a)

The difference between the distribution of bridge area and bridge count is the suspension bridge (8.82%) (Mount Hope and Claiborne Pell bridge) being the third largest bridge type in Rhode Island and box beam or girder (multiple) bridges (9.58%) being the second largest types in the United States. Also, the percentage for stringer/multi-beam or girder bridges in the United States regarding bridge area (62.15%) is noticeable higher than bridge count (40.23%) (FHWA 2018a).

6.1.4. Deck structures

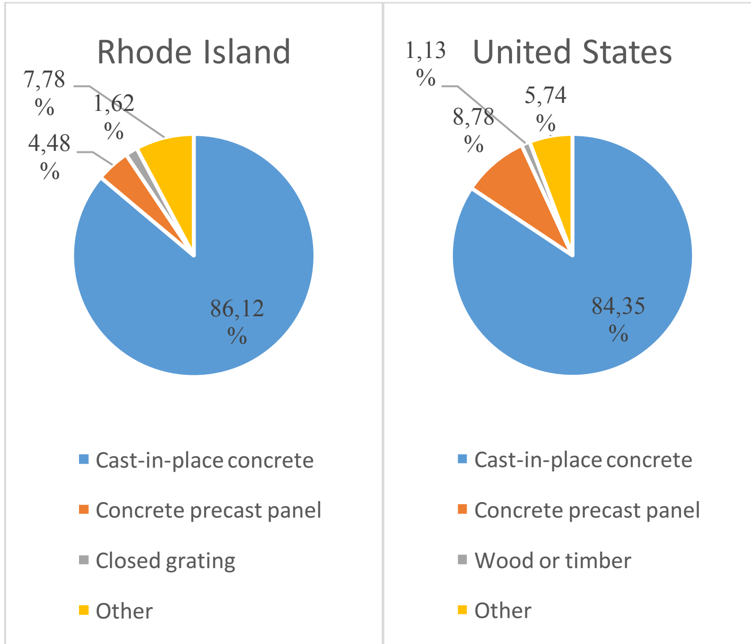
Graph 11 shows that the most used deck structures are cast in place concrete (Picture 13)(68.39% in Rhode Island, 59.29% in the United States), concrete precast panel (8.29% in Rhode Island, 10.00% in the United States) and wood or timber (4.02% in Rhode Island, 6.18% in the United States) (FHWA 2018a).



Graph 11: Most used deck structures by bridge count (%) (FHWA 2018a)

Compared to bridge area, shown in Graph 12, cast-in-place concrete is the predominant deck structure.

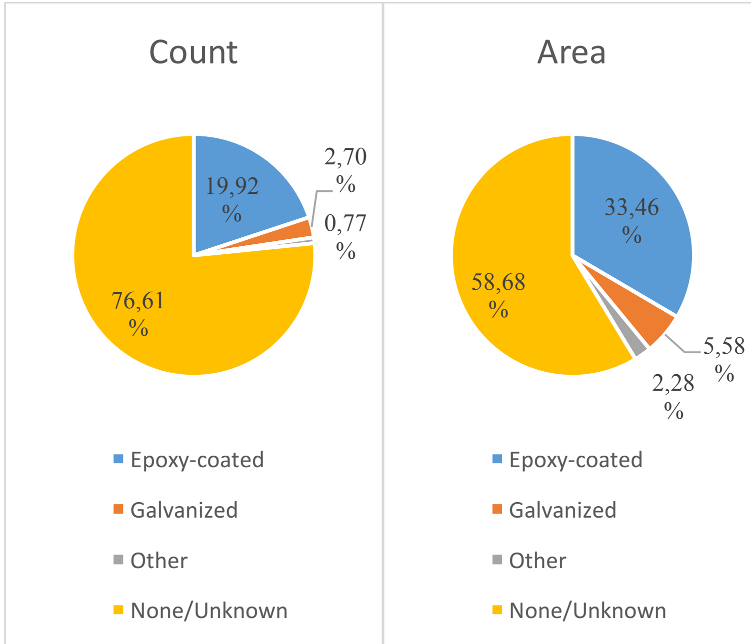
Picture 13: Cast-in-place concrete span 2 deck (Sellwood Bridge Project and Multnomah County, Oregon 2012)



Graph 12: Most used deck structures by bridge area (%) (FHWA 2018a)

The difference between bridge count and bridge area deck structures distribution can be seen in closed grating (1.62%) being the third largest deck structure by bridge area, other than wood or timber (4.02%) being the third largest deck structure by bridge count in Rhode Island.

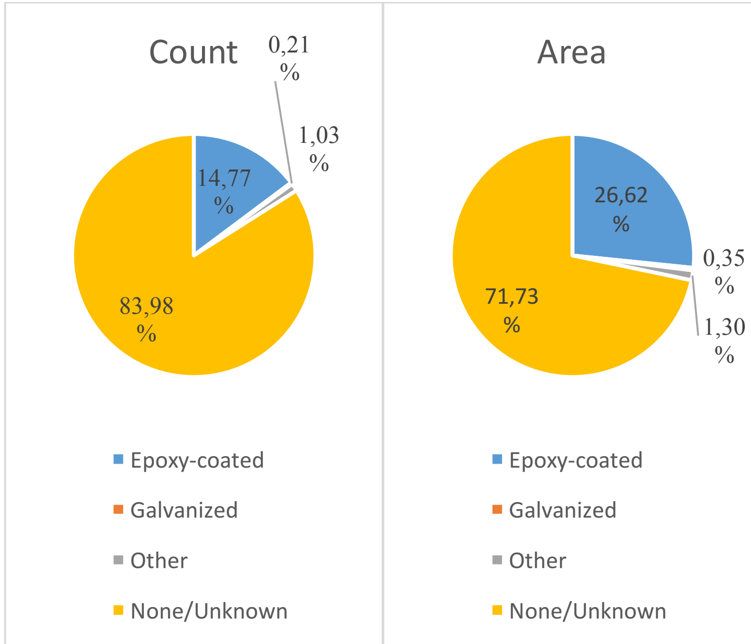
In regards of deck protection, the (FHWA 1995a) defines seven different types: epoxy coated reinforcing, polymer impregnated, galvanized reinforcing, cathodic protection, internally sealed, other coated reinforcing, unknown, and other deck protections. According to the bridge count, 23.39% of the total bridges in Rhode Island have a deck protection, in other words 76.61% have no or unknown deck protection, as Graph 13 shows. These number just slightly change in case of bridge area, 58.68% have no or unknown deck protection and 41.32% have a protection.



Graph 13: Deck protections by count and area in Rhode Island (%) (FHWA 2018a)

The most used deck protection system in Rhode Island is by far the epoxy-coated reinforcing (Count: 19.92%, Area: 33.46%). Just a small amount of bridge decks is protected by galvanized reinforcing (Count: 2.70%, Area: 5.58%) or other protection systems (Count: 0.77%, Area: 2.28%) (FHWA 2018a).

Comparing to the United States, shown in Graph 14, these numbers are similar.

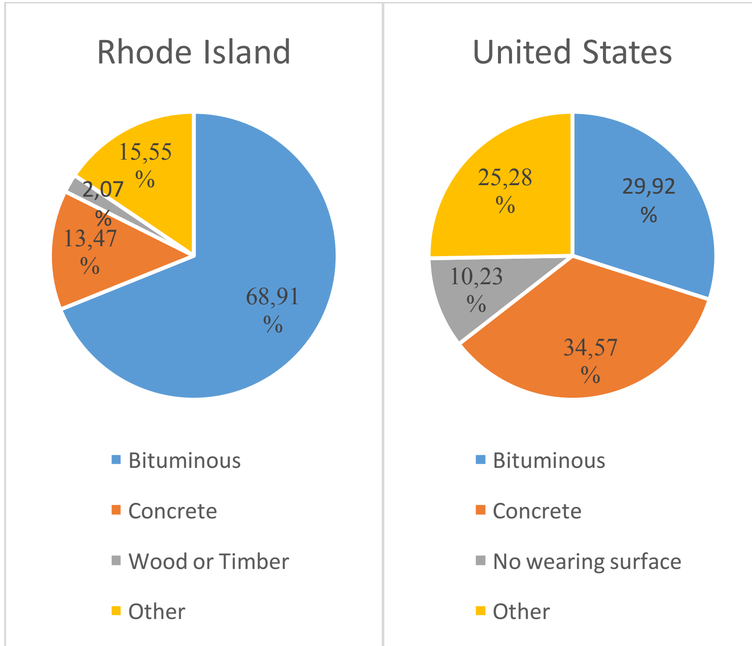


Graph 14: Deck protections by count and area in the United States (%) (FHWA 2018a)

The United States have 71.73% of bridge area without or with unknown deck protection (83.98% in case of bridge count). This number also includes all bridges without a deck. Just 26.62% have epoxy-coated reinforcement (14.77% in case of bridge count), and less then 2% of galvanized (0.35% area and 0.21% count) and other (1.30% area and 1.03% count) deck protections (FHWA 2018a).

6.1.5. Wearing surfaces

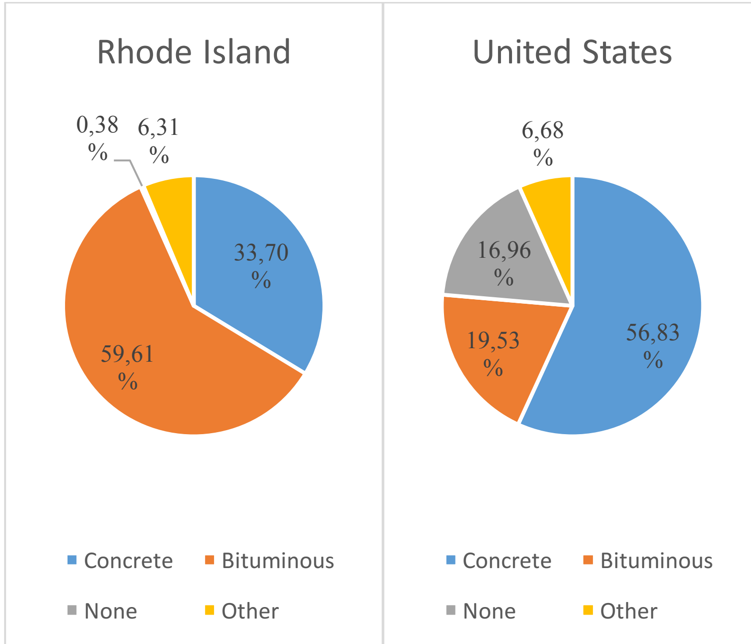
Wearing surfaces are defined by (FHWA 1995a) under nine different categories: monolithic concrete, integral concrete, latex concrete, low slump concrete, epoxy overlay, wood or timber, gravel, other, and bituminous wearing surfaces. For this study the first 4 wearing surfaces are grouped as concrete.



Graph 15: Most used wearing surface material by bridge count (%) (FHWA 2018a)

In the case of wearing surfaces, as Graph 15 shows, bituminous is the most used material in Rhode Island (68.91%). The second most used wearing surface materials are different kinds of concrete (13.47%), before wood or timber (2.07%) as third. Concrete (34.57%) is the most used and bituminous (29.92%) the second most used wearing surface material in the United States. However, 10.23% of the bridges in the United States have no wearing surface.(FHWA 2018a).

According to bridge area, shown in Graph 16, bituminous (59.61%) is the predominant wearing surface material by bridge area in Rhode Island, and just 0.38% of the bridge area in Rhode Island has no wearing surface.

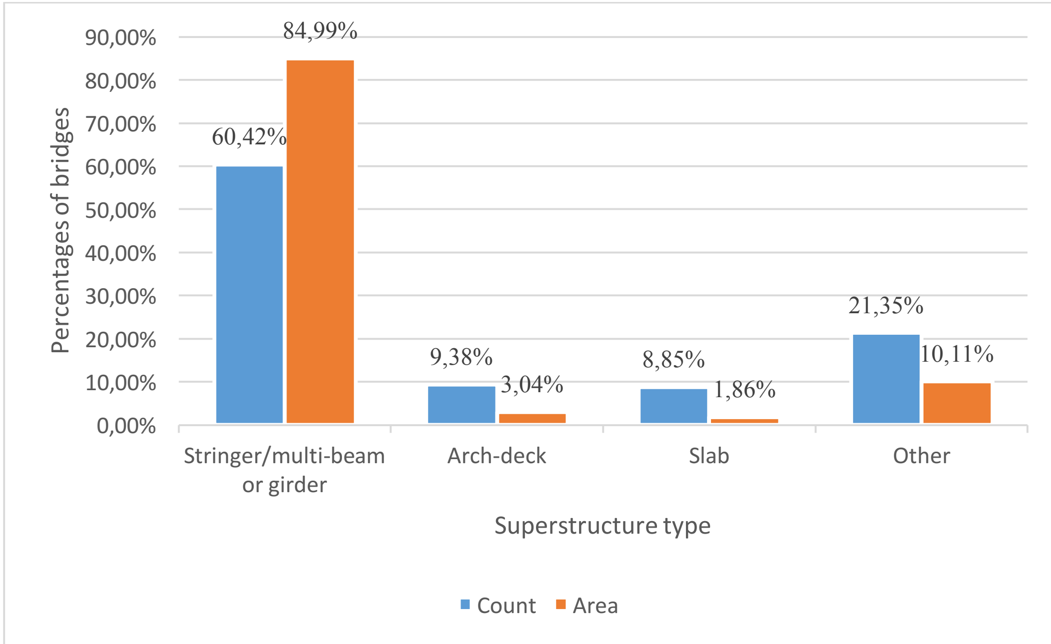


Graph 16: Most used wearing surface material by bridge area (%) (FHWA 2018a)

However, in the United States, the most used wearing surface material by bridge area is concrete (56.83%) and 16.96% of the bridge area in the United States has no wearing surface.

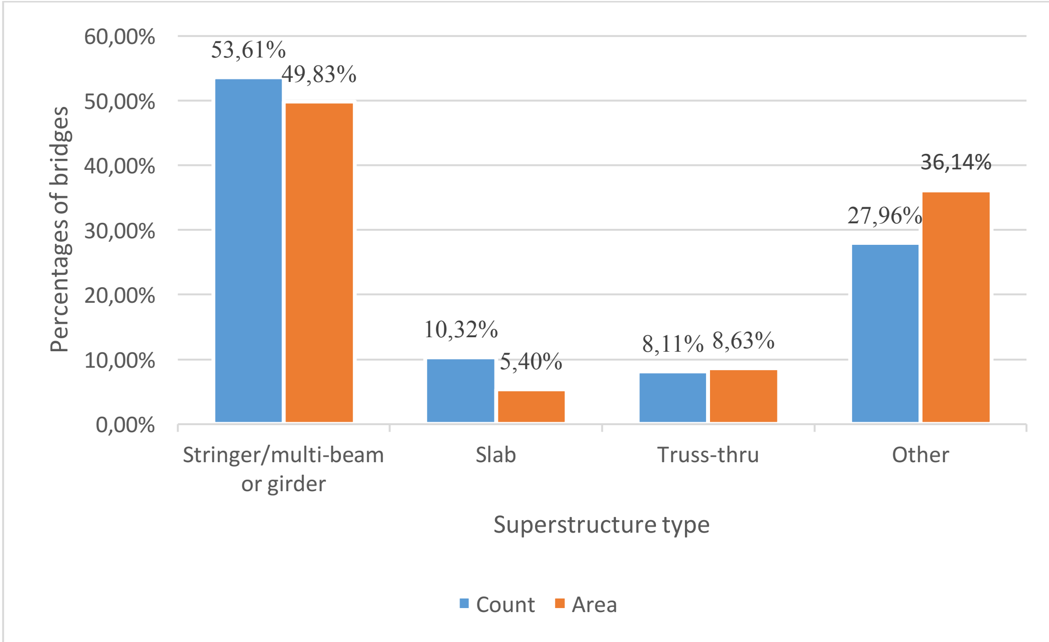
6.1.6. Superstructures

In the case of superstructure types the most used type stringer/multi-beam or girder bridge has also the highest number of structurally deficient bridges in Rhode Island (60.42%), as shown in Graph 17, and the United States (53.61%), as shown in Graph 18. In Rhode Island, the third most used type has the second highest number of structurally deficient bridges (Arch-deck 9.38%) and the fourth most used, slab bridges, has the third highest number (8.85%) of structurally deficient bridges. In the United States slab bridges (10.32%) are the second and truss-thru bridges (8.11%) are the third highest number of structurally deficient bridges (FHWA 2018a).



Graph 17: Structurally deficient bridges by superstructure type in Rhode Island (%) (FHWA 2018a)

Comparing structurally deficient superstructure types by count and area, stringer/multi-beam or girder (84.99%) is the predominant type in Rhode Island (FHWA 2018a).



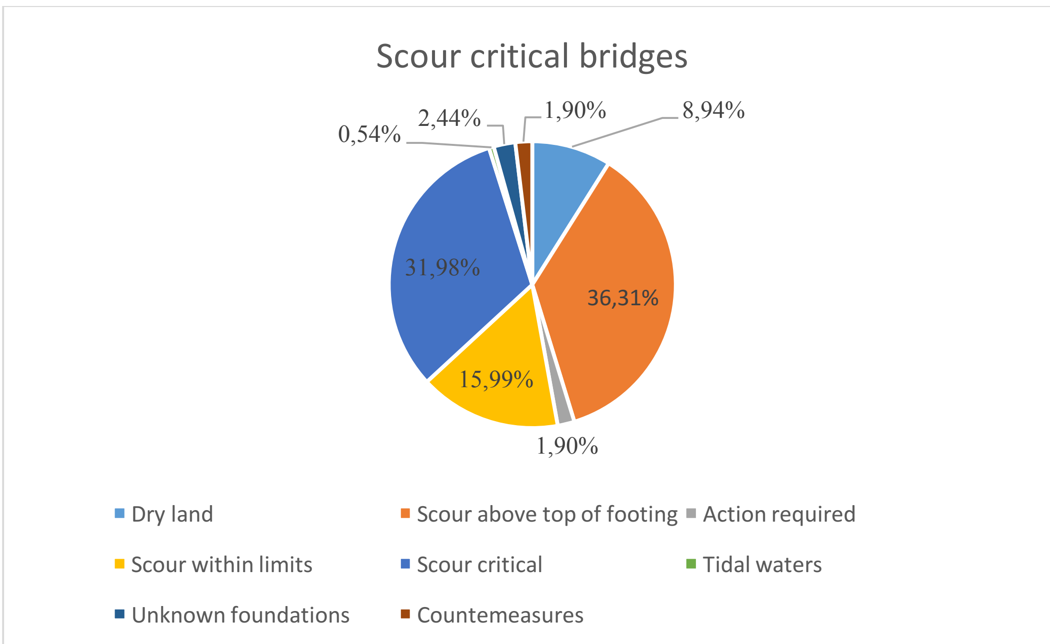
Graph 18: Structurally deficient bridges by superstructure type in the United States (%) (FHWA 2018a)

In the United States, stringer/multi-beam or girder (49.83%) are also the predominant structurally deficient superstructure type. However, the distribution of structurally deficiency for bridge count and area are closer in the United States than in Rhode Island (FHWA 2018a).

6.1.7. Substructure

In Rhode Island around 1.4% have a pier or abutment protection, such as fenders and dolphins, and around 3.7% do not require a protection. Around 94.5% is classified as not applicable, which indicates that "Item 38 – Navigation Control" – is also coded "not applicable". If navigation control is coded not applicable there is no waterway crossing the bridge. Of the 1.4% that have protection, 0.26% are in place but in a deteriorated condition, and 1.14% have protection in good condition. For 0.39% of the total bridges a protection is not present but reevaluation is suggested. The condition of the pier or abutment protection could be an influence for the overall substructure condition (FHWA 2018a).

“Item 113 – Scour critical bridges” can also have an effect on substructure condition and describes the vulnerability to scour. Around 52.6% are classified as “not over a waterway”. The remaining bridges, in total 369 bridges, are distributed as shown in Graph 19.

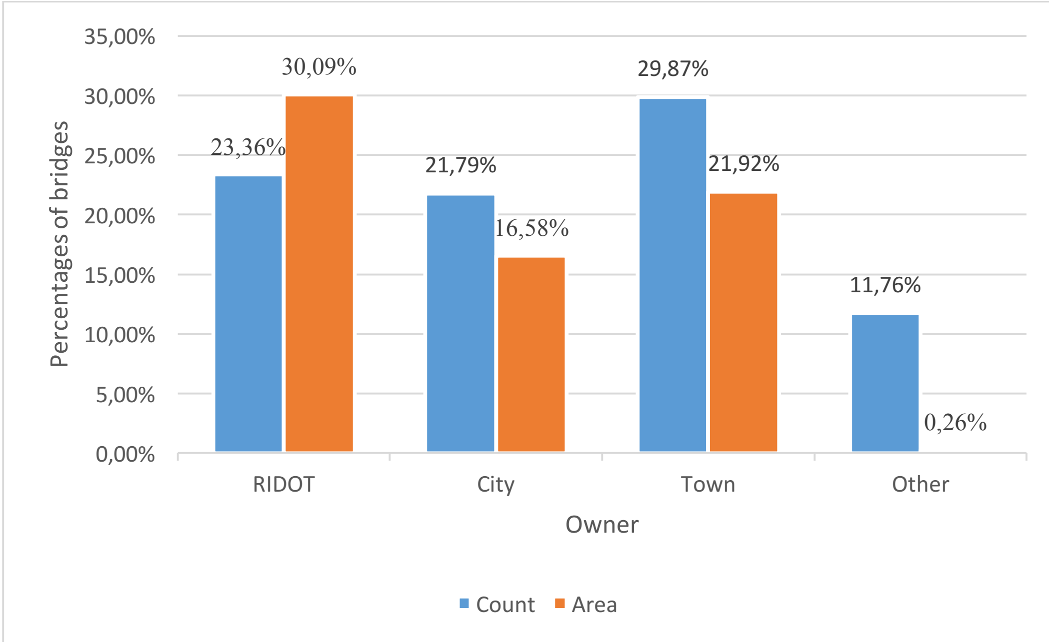


Graph 19: Scour critical bridges (%) (FHWA 2018a)

The bridge foundations are determined stable for calculated scour conditions, if scour is calculated above top of footing (36.31%), scour is within limits of footing or piles (15.99%), field reviews indicates that action is required to protect exposed foundations from additional erosion and corrosion (1.90%). In total 54.2% are classified stable for calculated scour conditions. Scour critical and bridge foundations determined to be unstable for calculated scour conditions, in case of scour within limits of footing or piles, and scour below spread-footing base or pile-tips, are 31.98%. The remaining 13.82% of bridges are bridges over tidal waters that have not been evaluated for scour but considered low risk (0.54%), have an unknown foundation that has not been evaluated for scour (2.44%), foundations are on dry land well above flood water elevations (8.94%), and have countermeasures to correct a previously existing problem with scour (1.90%) (FHWA 2018a).

6.1.8. Bridges by owner

The RIDOT owns around 76% (589 bridges, Area: 71.85%) of Rhode Island bridges, followed by cities or municipal highway agencies (Count: 10%, Area: 6.74%), towns and township highway agencies (Count 10%, Area: 1.68%). Small amounts of bridges are also owned by other owners, which are in total 34 bridges (Count 4%). However, in case of bridge area other owners own 19.74% of all bridges. The highest bridges area is owned by the state toll authority, accounting 92.38% of the 19.74% in total. Bridges owned by the RIDOT are in poor condition in 23.36% of the bridge counts and 30.09% regarding the bridge area, as shown in Graph 20 (FHWA 2018a).



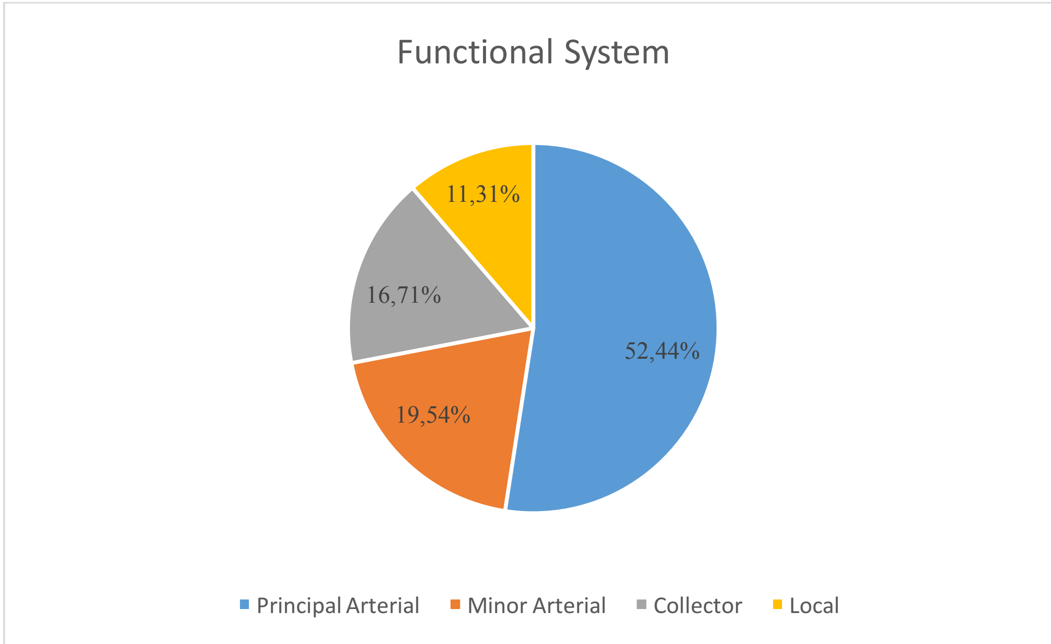
Graph 20: Bridges in poor condition by owner (%) (FHWA 2018a)

Of the total number of bridges owned by the city and municipality highway agencies, 21.79% are in poor condition, as well as 16.58% of the total bridge area owned. The town and township highway agencies have 29.87% of the bridge counts in poor condition and 21.92% of the bridge area. All other owners, including the state toll authority 11.76% of the bridge count are in poor condition, but only 0.26% of the bridge area, because 4 bridges of the state park, forest, or reservation agency are in poor condition which have an area of 416.48ft^2. Also displayed is the condition of bridges by ownership compared with the number of owned bridges, in Graph 20. The condition of the bridges in the state are not dependent on the ownership, due to similar percentages of poor bridges by owner compared with the amount of bridges owned. Just a slight difference can be seen between bridges owned by RIDOT, city agencies, and town agencies. The ownership also determines the maintenance responsibility for these bridges (FHWA 2018a).

6.1.9. Functional system

The functional system defines different volumes of traffic and mobility. The (FHWA 1995b) defines four groups of classification for functional systems: principal arterial, minor arterial, collector, and local. Principal arterials include interstate, freeway, and other expressway bridges. Minor arterials are connections to major arterials, but they are not as concentrated as principle arterials, including streets that allow faster speed limits. Collector systems provide local roads to traffic on arterial roads. Local roads are surface streets that are not collectors or arterials.

The distribution of bridges by functional class is shown in Graph 21. Most bridges are located on principal arterials (52.44%), such as interstates, freeways, and expressways.



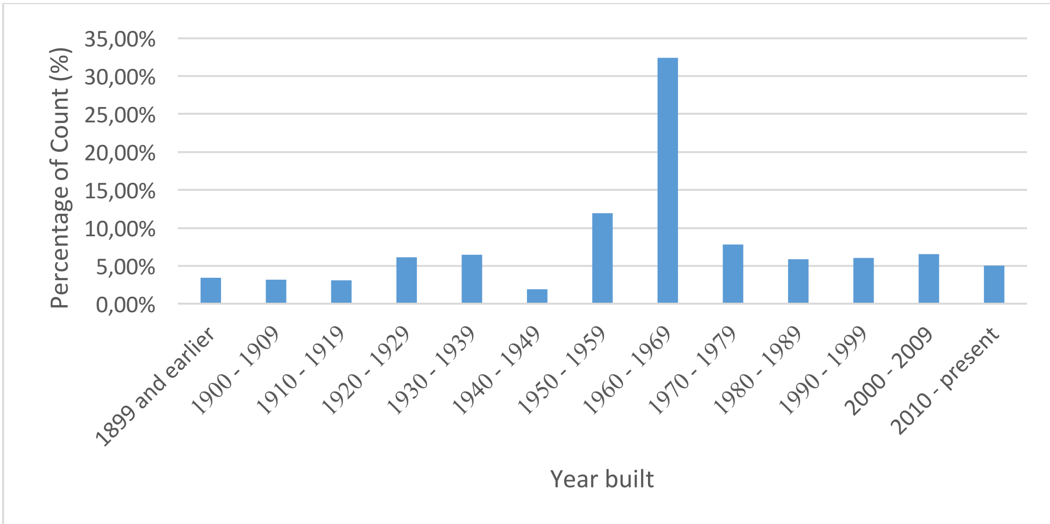
Graph 21: Bridges by functional system (%) (FHWA 2018a)

About 19.54% are located on minor arterials, followed by collector roads (16.71%) and local roads (11.31%).

6.1.10. Age distribution

Almost 64% percent (496 Bridges) of the state´s bridges in the NBI database are built in 1968 or before, making these bridges older than 50 years. Around 5.1% (40 bridges) of the younger bridges (Age 0-50 years) and 8.8% of bridge area (70377m^2) have a poor condition rating and 11.2% (87 bridges) are classified as good, with 14.2% of bridge area (113881m^2). Taking the older bridges (Age 50+ years) only 5.7% (44 bridges) are classified as good, with 2.1% bridge area (16651m^2), and 22.4% (141 bridges) are rated poor, with 14.4% bridge area (115030m^2) (FHWA 2018a).

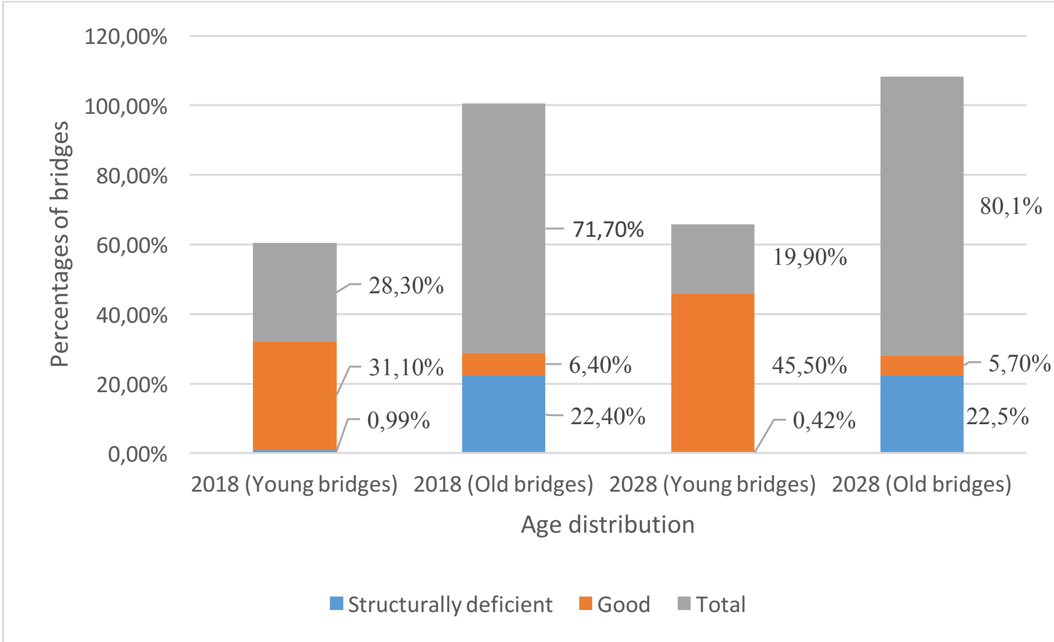
As shown in Graph 22, the majority of bridges were constructed between 1960-1969. These bridges are on the transition between being younger than the 50-year life-cycle expectancy and being older.



Graph 22: Percentages of total bridge count by year built (FHWA 2018a)

Due to many bridges approaching the 50-year lifespan or exceeding that age, the probability of deterioration and deficiency is higher. After the peak and major increase in bridge population, the number of bridges built decreased and stabilized around 5%.

Graph 23 shows the distribution of structurally deficient bridges for young and old bridges, as well as good condition and the total amount.



Graph 23: Young and old bridges and their condition in Rhode Island (%) (FHWA 2017d)

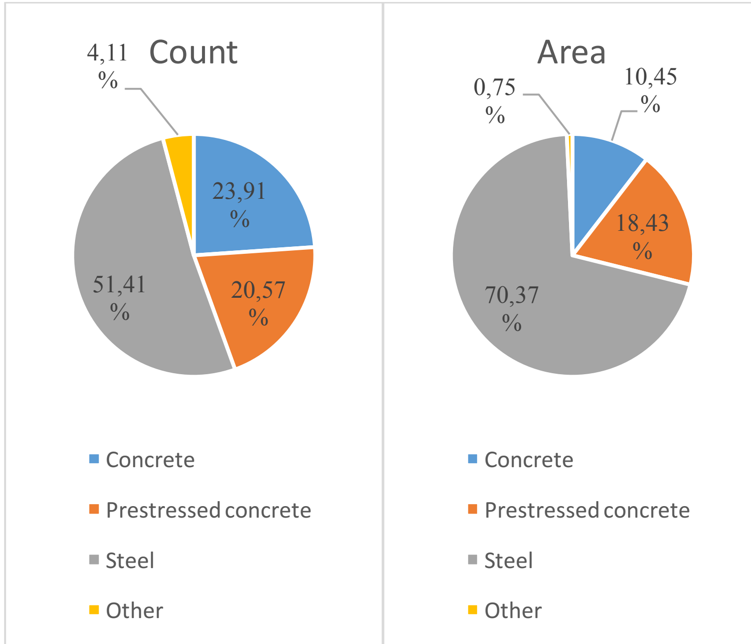
For this graph, young bridges are defined 48 years old or younger and old bridges 49 years and older. In 2018 71.70% are classified as old and 28.30% as young. Out of all old bridges 6.40% are good, which means a condition rating of 5 or higher in the FHWA rating scale, and 22.40% structurally deficient. The distribution for young bridges is 31.10% good and 0.99% structurally deficient. The numbers for 2028 are predicted by assuming the condition of the bridges will not change, which is unlikely. However, the numbers still show an increase of 8.4% old bridges, of which 22.5% would be structurally deficient and 5.7% good. The amount of young bridges would decrease to 19.90% and just 0.42% of them would be structurally deficient. The amount of good young bridges in 2028 would be 45.50%. The numbers show just a slight difference in the condition distribution, but an increase in old bridges and thus a higher amount of structurally deficient bridges with nearly the same percentage.

6.1.11. Material composition

The main structure material is defined by (FHWA 1995a) in 10 different material types:

- Aluminum, wrought iron, or cast iron
- Concrete
- Concrete continuous
- Masonry
- Other
- Prestressed concrete
- Prestressed concrete continuous
- Steel
- Steel continuous
- Wood or timber

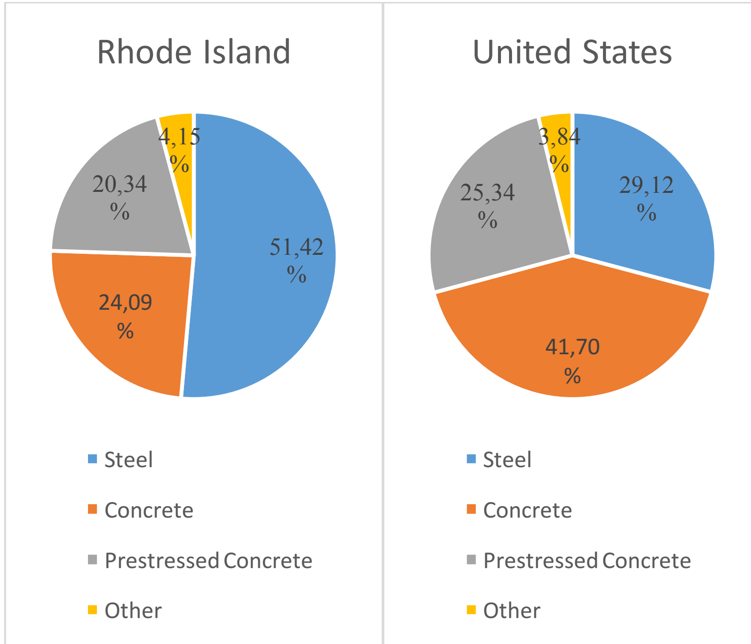
For this study, these materials are grouped in concrete, prestressed concrete, steel, and other. The composition of materials can be seen in Graph 24 (FHWA 2018a).



Graph 24: Material composition (FHWA 2018a)

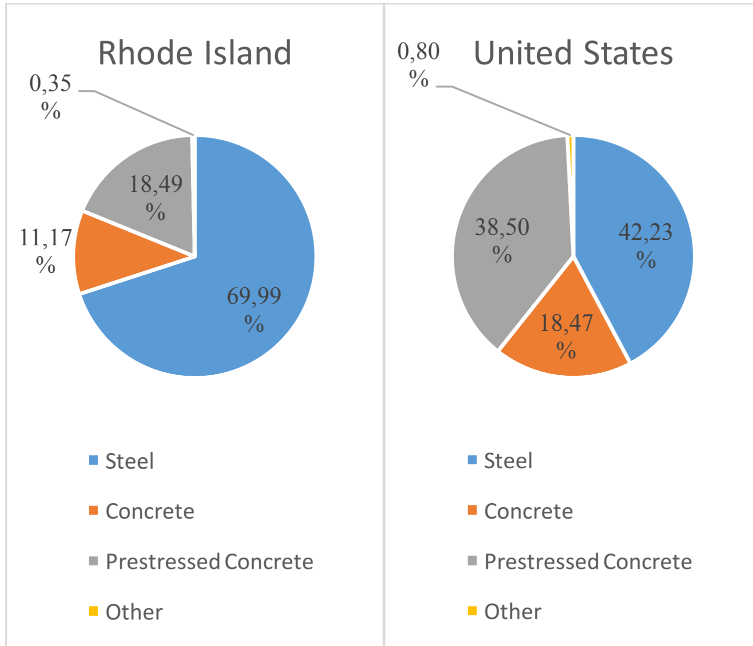
More than half of the bridges in case of bridge count in Rhode Island are composed of steel. This number is even higher for the bridge area (70.37%). The rest is split between concrete (Count: 23.91%, Area: 10.45%), prestressed concrete (Count: 20.57%, Area: 18.43%), and other materials (Count: 4.11%; Area: 0.75%). When analyzing this graph, steel is the leading material used, closely followed by concrete (FHWA 2018a).

The most used superstructure material in Rhode Island is steel (51.42%), followed by concrete (24.09%), and prestressed concrete (20.34%). Taking the total number of bridges in the United States concrete (41.70%) is the most used superstructure material, followed by steel (29.12%), and prestressed concrete (25.34%), as shown in Graph 25 (FHWA 2018a).



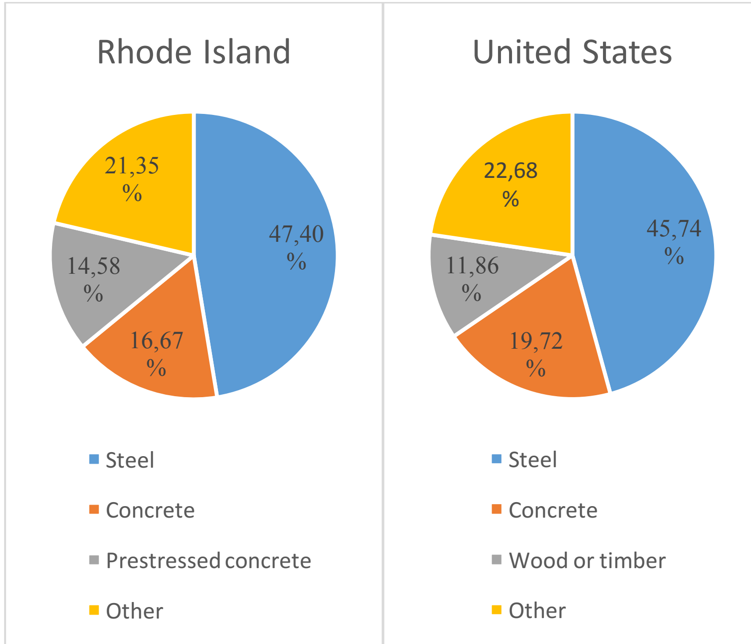
Graph 25: Most used superstructure material by bridge count (%) (FHWA 2018a)

Similar percentages can be seen for bridge deck area in case of superstructure material, shown in Graph 26. Steel is the most used material (69.99%), followed by prestressed concrete (18.49%), and concrete (11.17%). Compared with the United States, steel is still the most used material (42.23%), but closely followed by prestressed concrete (38.50%). Concrete has 18.47% in case of bridge deck area in the United States (FHWA 2018a).



Graph 26: Most used superstructure material by bridge area (%) (FHWA 2018a)

Most of the structurally deficient bridges in Rhode Island (47.40%), and the United States (45.74%) have a steel superstructure, followed by concrete (16.67% in Rhode Island, 19.72% in the United States), as shown in Graph 27.



Graph 27: Structurally deficient bridges by superstructure material deck area (%) (FHWA 2018a)

In Rhode Island prestressed concrete (14.58%) is third, in the case of structurally deficient superstructure materials. However, in the United States there are more structurally deficient bridges with a wood superstructure (11.86%) than prestressed concrete (8.55%).

6.1.12. Average daily traffic

Bridges with the highest average daily traffic (ADT) have a higher probability of deterioration, because of the traffic impact. Figure 15 shows a map of Rhode Island with the ADT per bridge.

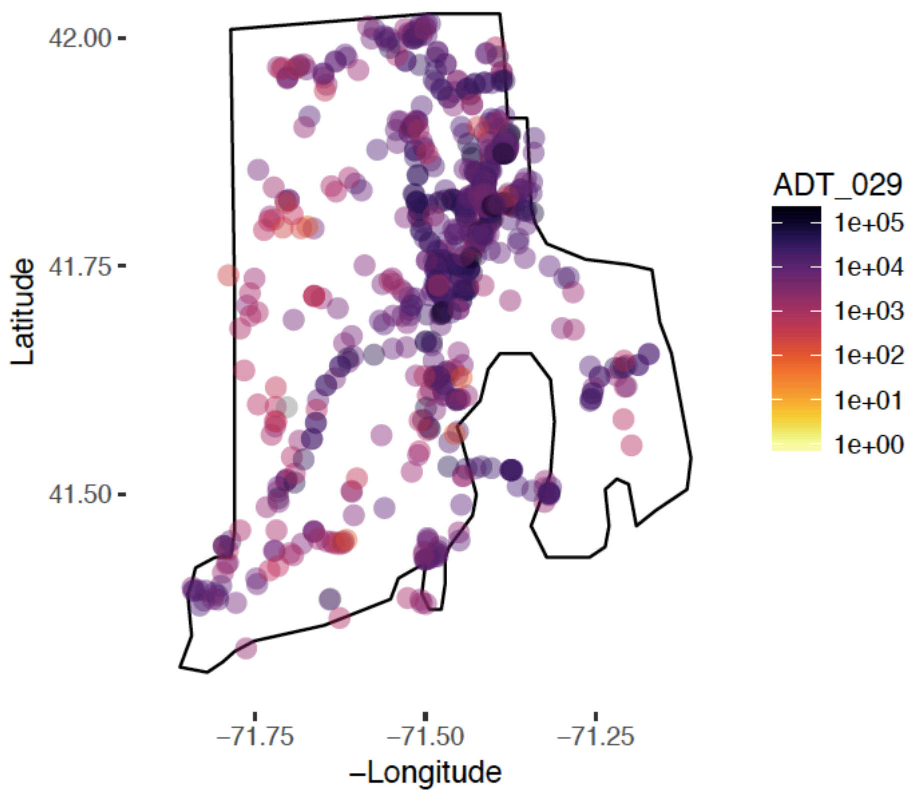


Figure 15: Average daily traffic for Rhode Island bridges (FHWA 2018a)

It is noticeable that bridges at certain corridors have a higher ADT and bridges outside this corridor have lower ADT. That means bridges at traffic corridors have a higher probability of deterioration and thus need more attention in case of preservation. The most travelled structurally deficient bridges can be seen in Table 7.

Table 7: Most travelled structurally deficient bridges (FHWA 2018a)

Structure Number	Place code	Bridge Description	Owner	ADT
00095	Providence City	'US 6 WOON RVR AMTRAK '	State Highway Agency	171707
00095	Providence City	'BLACKSTONE ST '	State Highway Agency	167639
00095	Providence City	'US 1 ELMWOOD AV '	State Highway Agency	157769
00095	Providence City	'AMTRAK '	State Highway Agency	157769
00095	Cranston City	'WELLINGTON AV '	State Highway Agency	157769
00195	East Providence City	'SEEKONK RIVER '	State Highway Agency	76700
00006	Providence City	'PLAINFIELD ST '	State Highway Agency	70690
00146	North Providence Town	'RI 15 MINERAL SPRING AV '	State Highway Agency	69109
00146	Providence City	'BRANCH AV '	State Highway Agency	67584
00006	Providence City	'US 6A HARTFORD AV '	State Highway Agency	59930

All of the most travelled structurally deficient bridges are in Providence County and owned by the state highway agency. Most of them are in Providence City and half of them have an ADT of more than 150,000.

6.1.13. Future condition ratings

Compared with the numbers of the Rhode Island Department of Transportation (RIDOT) 360 bridges of 1,193 bridges (30%) are rated with a four in the NBI rating or less which indicates a poor condition. This number increases by 11% to 491 bridges (41%) in 10 years from now, as shown in Figure 16 (RIDOT personnel 2018). The RIDOT is considering all bridges in the state (1,193 Bridges) and not only the bridges defined by the NBIS. However, for all analysis in the following thesis, data from the NBI is used.

Network NBI Rating distributions

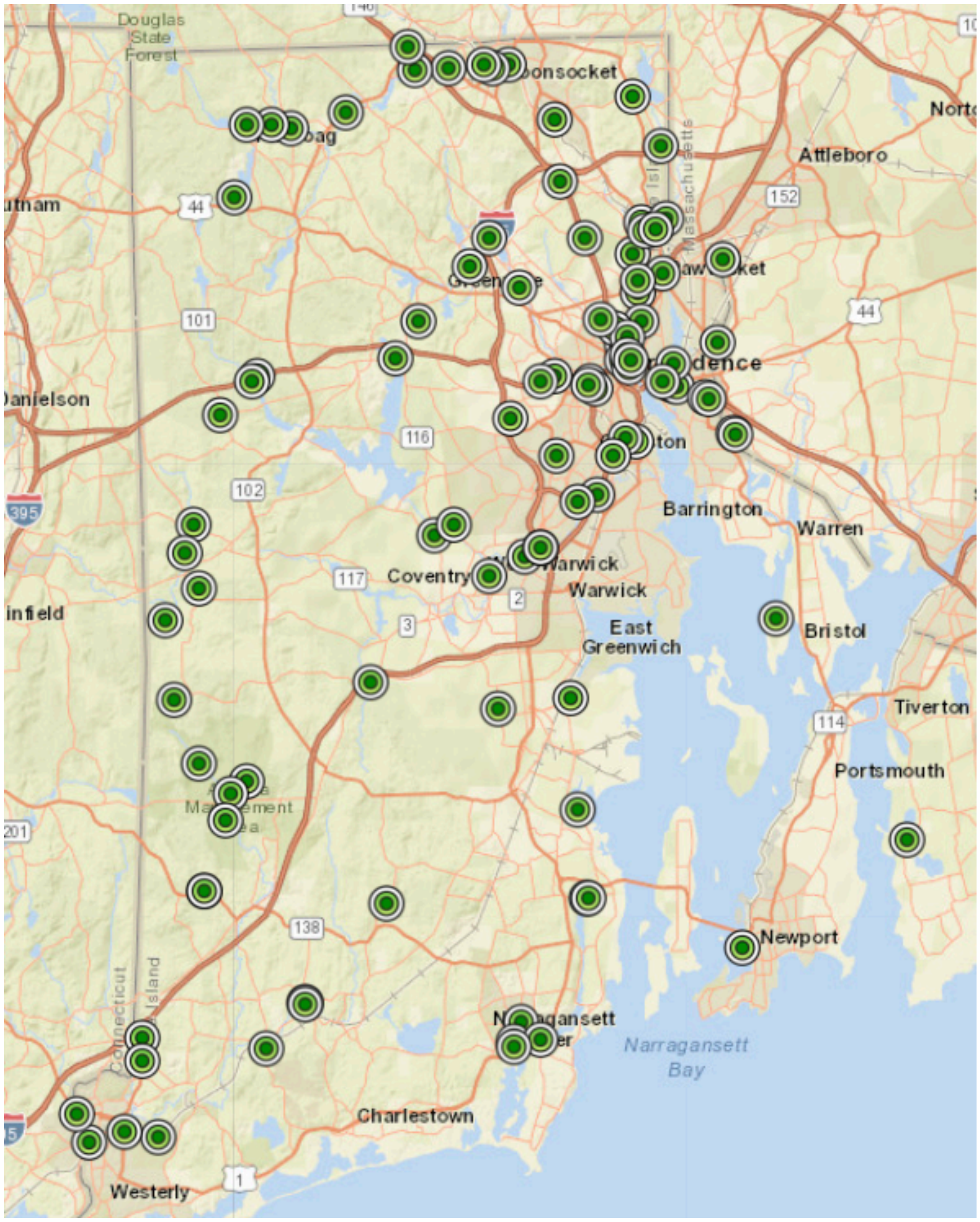
Bridge Filter: Entire Network ▼ Re-estimate results

Component: Bridge-Level ▼

	Latest Inspection Reported	Current	+5 Years	+10 Years
NBI Rating 9	1	0	0	0
NBI Rating 8	20	21	21	18
NBI Rating 7	242	219	173	123
NBI Rating 6	324	251	263	270
NBI Rating 5	367	342	344	275
NBI Rating 4	166	237	231	191
NBI Rating 3	59	93	81	213
NBI Rating 2	11	21	61	53
NBI Rating 1	1	9	17	34

Figure 16: Rating of Rhode Island bridges by RIDOT (RIDOT personnel 2018)

Of all structurally deficient bridges in the NBI database there are 101 bridges open, 59 posted and 7 closed. Picture 14 shows all posted bridges in Rhode Island (FHWA 2017e).



Picture 14: Location of posted bridges in Rhode Island (RIDOT 2018b)

That makes Rhode Island bridges ranked last in the ranking of all states, also in case of the sufficiency ranking. The sufficiency ranking is based on a formula that measures the condition, functionality and importance of the structure (Rocheleau, Matt 2014).

6.2. Performance measures

The performance measures authored are based on NBI data and NBI element data which were merged with the program R. However, not every bridge has data in both datasets. Table 8 shows the distribution of bridges in the NBI database and in the NHS system, as well as bridges with element level data, and NHS bridges with element data. This study focusses on the NHS bridges with element data.

Table 8: Number of bridges and their source

	Source	Count	Deck Area
NHS Bridges	NBI	418	632.772
All Bridges with BE Reports	NBIBE	647	684.231
NHS Bridges with BE Reports	NBI-NBIBE	347	554.826

The NHS bridges with NBI element data are 347 in count and have a deck area of 554,826 ft^2. These bridges are used to evaluate performance measures.

6.2.1. Filtered performance measures

Before these performance measures can be evaluated, the bridges will be filtered by constructed, reconstructed, improved bridges in the last 10 years. Table 9 shows the bridges and their amount of good, at-risk and poor bridge elements areas for the three options. A table of the same information with bridge counts can be found in Appendix 4.

Table 9: Bridges constructed, reconstructed, improved in the last 10yrs

Element to preserve	Element affecting exposure	Measure of Preservation	Last 10 years									Reference Number
			Constructed			Reconstructed			Imrpoved			
			Good	At Risk	Poor	Good	At Risk	Poor	Good	At Risk	Poor	
NBE	BME	NBE deck, superstructure, substructure, and culvert relative to BME, joints, coatings, and wearing surfaces	184.609	14.871	213	315.910	53.178	1.554	250.230	57.970	11.891	1
NBE deck	BME	NBE deck relative to BME joints, coatings, and wearing surfaces	184.218	14.871	0	315.460	53.178	0	259.257	60.298	164	2
NBE superstructure	BME	NBE superstructure relative to BME joints, coatings, and wearings surfaces	184.822	14.871	0	315.910	53.178	1.554	250.138	57.970	11.891	3
NBE substructure	BME	NBE substructure relative to BME joints, coatings, and wearing surfaces	184.609	14.871	213	17.463	53.178	0	259.227	60.117	655	4
NBE culvert	BME	NBE culvert relative to BME joints, coatings, and wearing surfaces	0	0	0	0	0	0	293	0	250	5
NBE concrete	BME	NBE concrete (continuous) deck, superstructure, substructure, and culvert relative to BME joints, coatings, and wearing surfaces	4.096	0	0	11.663	0	0	0	0	559	6
NBE prestressed concrete	BME	NBE prestressed concrete (continuous) deck, superstructure, substructure, and culvert relative to BME joints, coatings and wearing surfaces	16.087	2.181	213	209.491	50.651	1.554	204.410	50.651	1.072	7
NBE steel	BME	NBE steel (continuous) deck, superstructure, substructure, and culvert relative to BME joints, coatings, and wearing surfaces	164.426	12.640	0	94.755	2.527	0	45.714	7.319	10.260	8
NBE timber	BME	NBE timber deck, superstructure, substructure, and culvert relative to BME joints, coatings, and wearing surfaces	0	49	0	0	0	0	0	0	0	9
NBE Aluminium, Wrought Iron, Cast Iron	BME	NBE aluminium, wrought iron, and cast iron deck, superstructure, substructure, and culvert relative to BME joints, coatings, and wearing surfaces	0	0	0	0	0	0	0	0	0	10
NBE concrete	BME coating	Concrete (continuous) NBE relative to BME concrete coatings. Parent element IDs are enforced.	0	0	0	0	0	0	0	0	0	11
NBE steel	BME coating	Steel NBErelative to BME steel coatings. Parent element IDs are enforced.	106.647	132	0	31.370	1.263	0	28.624	2.542	5.130	12
NBE deck	BME wearing surface	NBE decks relative to BME wearing surfaces. Parent element IDs are enforced.	30.976	0	0	65.124	0	0	59.822	209	82	13
NBE	BME joint	NBE deck , superstructure, substructure, and culvert relative to BME joints	36.812	14.739	106	107.944	51.177	777	60.625	54.831	4.203	14
NBE deck	BME joint	NBE decks relative to joints	36.717	14.739	0	107.719	51.177	0	64.391	55.268	0	15
NBE superstructure	BME joint	NBE superstructure relative to BME joints	36.918	14.739	0	107.944	51.177	777	60.626	54.831	4.203	16
NBE substructure	BME joint	NBE substructure relative to BME joints	36.812	14.739	106	108.721	51.177	0	64.391	54.831	437	17
NBE concrete	BME joint	NBE concrete (continuous) deck, superstructure, substructure, and culvert relative to BME joints	1.982	0	0	4.581	0	0	0	0	192	18
NBE prestressed concrete	BME joint	NBE prestressed concrete (continuous) deck, superstructure, substructure, and culvert relative to BME joints	8.888	2.181	106	54.690	50.651	777	50.975	50.651	645	19
NBE steel	BME joint	NBE steel (continuous) deck, superstructure, substructure, and culvert relative to BME joints	25.943	12.508	0	48.672	526	0	9.651	4.180	3.365	20
NBE timber	BME joint	NBE timber deck, superstructure, substructure, and culvert relative to BME joints	0	49	0	0	0	0	0	0	0	21
NBE	BME joint, open	NBE deck , superstructure, substructure, and culvert relative to BME open joints	132	0	0	0	0	0	0	0	1.683	22
NBE	BME joint, other	NBE deck , superstructure, substructure, and culvert relative to BME other joints	4.595	727	0	9.483	0	388	2.466	710	0	23
NBE	BME joint, assembly without seal	NBE deck , superstructure, substructure, and culvert relative to BME assembly without seal joints	0	0	0	50.651	0	0	53.596	0	1.683	24
NBE	BME joint, assembly with seal (modular)	NBE deck, superstructure, substructure, and culvert relative to BME assembly with seal (modular) joints	13.817	7.387	0	11.103	50.651	0	0	50.651	0	25
NBE	BME joint, compression	NBE deck , superstructure, substructure, and culvert relative to BME compression joints	1.958	727	0	2.920	0	0	596	0	218	26
NBE	BME joint, strip seal	NBE deck , superstructure, substructure, and culvert relative to BME strip seal joints	8.242	5.121	0	15.412	0	0	0	2.944	0	27
NBE	BME joint, pourable	NBE deck , superstructure, substructure, and culvert relative to BME pourable joints	8.069	777	106	18.375	526	388	3.967	526	619	28

The table also includes reference numbers (RN), a description on the measure of preservation, the exposure elements and preservation elements. The numbers for bridges at-risk or in poor condition are showing a fast deterioration of these bridges or a insufficient rehabilitation and could be analyzed separately. For this study the number for bridges in good condition are important, because the majority of these bridges are expected to be in good condition because of the young age or rehabilitation in the last years. Therefore, the number of good bridges which are constructed, reconstructed or improved during the last 10 years are subtracted from the overall bridges in good condition for each reference number. Appendix 5 shows the performance measures with all bridges included, as well as bridge count in Appendix 6 and bridge area in Appendix 7, before subtracting. Table 10 shows the performance measures for all bridges subtracted good bridges of the last 10 years. Tables for bridge count and bridge area can be found in Appendices 8 and 9. Compared with the original table in Appendix 10, a slight decrease of percentages for good bridges by area and a slight increase in percentages for at-risk and poor bridges by area can be seen. The decrease of good bridges, 5.71% for bridge area (RN 25) and has a median of 1.60%. The increase for at-risk bridges peeks at 4.88% (RN 25) and has a median of 1.02%. The maximum increase for poor bridges is 1.44% (RN 18) and the median 0.58%. The increase of at-risk bridges in total is 28.61% and for poor bridges 16.17%. The RN 25 are all NBEs in relation to BME assembly with seal (modular) joints and RN 18 all NBE concrete (continuous) NBEs in relation to BME joints.

Table 10: Performance measures for Rhode Island bridges

Element to preserve	Element affecting exposure	Measure of Preservation	Preservation performance (%)						Reference Number
			Area			Count			
			Good	At-risk	Poor	Good	At-risk	Poor	
NBE	BME	NBE deck, superstructure, substructure, and culvert relative to BME, joints, coatings, and wearing surfaces	47,44%	27,29%	25,27%	48,69%	21,95%	29,36%	1
NBE deck	BME	NBE deck relative to BME joints, coatings, and wearing surfaces	55,73%	36,85%	7,42%	59,40%	33,44%	7,16%	2
NBE superstructure	BME	NBE superstructure relative to BME joints, coatings, and wearings surfaces	52,00%	30,41%	17,58%	52,97%	25,50%	21,53%	3
NBE substructure	BME	NBE substructure relative to BME joints, coatings, and wearing surfaces	53,80%	32,45%	13,75%	57,88%	30,77%	11,36%	4
NBE culvert	BME	NBE culvert relative to BME joints, coatings, and wearing surfaces	97,06%	0,00%	2,94%	80,00%	0,00%	20,00%	5
NBE concrete	BME	NBE concrete (continuous) deck, superstructure, substructure, and culvert relative to BME joints, coatings, and wearing surfaces	53,88%	20,19%	25,92%	53,45%	14,94%	31,61%	6
NBE prestressed concrete	BME	NBE prestressed concrete (continuous) deck, superstructure, substructure, and culvert relative to BME joints, coatings and wearing surfaces	70,13%	19,38%	10,49%	60,11%	19,66%	20,22%	7
NBE steel	BME	NBE steel (continuous) deck, superstructure, substructure, and culvert relative to BME joints, coatings, and wearing surfaces	44,23%	28,61%	27,16%	46,35%	23,18%	30,47%	8
NBE timber	BME	NBE timber deck, superstructure, substructure, and culvert relative to BME joints, coatings, and wearing surfaces	74,27%	2,65%	23,07%	64,29%	7,14%	28,57%	9
NBE Aluminum, Wrought Iron, Cast Iron	BME	NBE aluminium, wrought iron, and cast iron deck, superstructure, substructure, and culvert relative to BME joints, coatings, and wearing surfaces	0,00%	0,00%	100,00%	0,00%	0,00%	100,00%	10
NBE concrete	BME coating	Concrete (continuous) NBE relative to BME concrete coatings. Parent element IDs are enforced.	82,49%	9,29%	8,22%	70,59%	17,65%	11,76%	11
NBE steel	BME coating	Steel NBErelative to BME steel coatings. Parent element IDs are enforced.	43,95%	33,26%	22,79%	42,62%	26,18%	31,20%	12
NBE deck	BME wearing surface	NBE decks relative to BME wearing surfaces. Parent element IDs are enforced.	77,45%	11,16%	11,39%	81,17%	10,61%	8,22%	13
NBE	BME joint	NBE deck , superstructure, substructure, and culvert relative to BME joints	41,57%	31,11%	27,33%	44,71%	27,65%	27,65%	14
NBE deck	BME joint	NBE decks relative to joints	50,39%	42,36%	7,25%	53,90%	39,78%	6,32%	15
NBE superstructure	BME joint	NBE superstructure relative to BME joints	47,49%	33,41%	19,10%	48,74%	30,99%	20,26%	16
NBE substructure	BME joint	NBE substructure relative to BME joints	48,23%	36,69%	15,08%	52,51%	36,64%	10,85%	17
NBE concrete	BME joint	NBE concrete (continuous) deck, superstructure, substructure, and culvert relative to BME joints	35,96%	35,84%	28,20%	41,30%	23,91%	34,78%	18
NBE prestressed concrete	BME joint	NBE prestressed concrete (continuous) deck, superstructure, substructure, and culvert relative to BME joints	51,37%	38,53%	10,10%	50,61%	32,93%	16,46%	19
NBE steel	BME joint	NBE steel (continuous) deck, superstructure, substructure, and culvert relative to BME joints	39,62%	29,33%	31,05%	42,96%	26,48%	30,56%	20
NBE timber	BME joint	NBE timber deck, superstructure, substructure, and culvert relative to BME joints	76,54%	5,66%	17,80%	66,67%	16,67%	16,67%	21
NBE	BME joint, open	NBE deck , superstructure, substructure, and culvert relative to BME open joints	37,88%	0,00%	62,12%	52,63%	0,00%	47,37%	22
NBE	BME joint, other	NBE deck , superstructure, substructure, and culvert relative to BME other joints	36,92%	22,59%	40,49%	52,35%	31,18%	16,47%	23
NBE	BME joint, assembly without seal	NBE deck , superstructure, substructure, and culvert relative to BME assembly without seal joints	63,84%	10,76%	25,41%	35,29%	14,71%	50,00%	24
NBE	BME joint, assembly with seal (modular)	NBE deck, superstructure, substructure, and culvert relative to BME assembly with seal (modular) joints	39,79%	51,40%	8,81%	50,00%	22,22%	27,78%	25
NBE	BME joint, compression	NBE deck , superstructure, substructure, and culvert relative to BME compression joints	32,54%	54,10%	13,36%	50,75%	28,36%	20,90%	26
NBE	BME joint, strip seal	NBE deck , superstructure, substructure, and culvert relative to BME strip seal joints	29,41%	49,99%	20,60%	52,73%	27,27%	20,00%	27
NBE	BME joint, pourable	NBE deck , superstructure, substructure, and culvert relative to BME pourable joints	41,70%	24,43%	33,86%	39,30%	30,50%	30,21%	28

The highest amount of at-risk bridges can be found by RN 26 (54.10%), which are NBEs related to BME compression joints. The second highest percentage for bridges at-risk has RN 25 (51.40%), the NBEs in relationship to BME assembly with seal (modular) joints. In case of good bridges, RN 5, NBE culverts in relationship to BMEs has the highest percentage (97.06%). Comparing bridges in poor condition, RN 10, NBE aluminum, wrought iron, or cast iron in relationship to all BMEs has the highest percentage (100%), followed by RN 22, all NBEs in relation to BME open joints (62.12%).

Comparing different BME and NBE groups, the substructure has the highest median (34.57%), the superstructure the second highest median (31.91%), and the deck the third highest median (30.12%). In case of materials, steel has the highest median percentage (30.40%), followed by prestressed concrete (28.95%), and concrete (21.78%). For BME groups, the joints have the highest at-risk median (31.08%), and coating the second highest (21.27%). Overall, bridge preservation is good for 47.44% of all reported NHS bridges.

6.2.2. Cost and time estimations for preservation programs

In this section, the results of Chapter 6.2.1 and equations of Chapter 5.3 are applied to estimate the cost and time of a Rhode Island preservation program. This should illustrate an example of how to use the preservation performance measures authored. The cost of preservation is computed by using average construction cost of preservation activities. In this example it is assumed that there are no additional costs for the user, like detour. Also, the costs are not adjusted due to time, which means that no inflation factor is used, as well as no interest factor. Other possible adjustment could be done for different materials. This limited example is to show cost and time estimations for preservation programs to give the basis for a comparison with replacement programs and to help with the decision process.

At first the preservation need is calculated. Suitable for the Equation 1 are all bridges that are at-risk to deteriorate into poor condition. Table in appendix shows that 27.29% of the bridge area has an at-risk condition. According to Table 8 all NHS bridges with element data have a bridge area of 554,826 ft^2. The total bridge area with an at-risk condition equals to 151,412 ft^2. The preservation interval based on Hearn et al. (2013) is determined by service intervals for Colorado bridges. Therefore, the sum of the median years a bridge remains at each NBI rating condition from nine to six, and plus one-half of the median years at a condition rating of five is used to compute the service interval (Hearn et al. 2013).

$$(1) \qquad Preservation\ need = \frac{151{,}412\ ft^2}{64\ yrs} = 2{,}366\ {}^{ft^2}/_{yr}$$

$$(1) \qquad Preservation\ need = \frac{347\ bridges}{64\ yrs} \approx 6\ {}^{bridges}/_{yr}$$

The cost associated with preservation are calculated by using the average cost obtained by Chapter 4. An average of 2,366 ft^2/yr needs to be preserved to keep bridges in a good to fair condition. Using the preservation need and the average cost of preservation, the preservation cost becomes:

$$(2) \qquad Preservation\ cost = 2{,}366\ {}^{ft^2}/_{yr} \times {}^{\$425}/_{ft^2} = {}^{\$1{,}005{,}550}/_{yr}$$

To keep at-risk bridges in a good to fair condition, \$1,005,550/yr are needed for preservation.

6.2.3. Preservation program

The Equations 4 to 7 in Chapter 5.3 can then be used to further evaluate the preservation performance. For this example, a preservation program for bridge joint preservation is calculated. With Equation 4:

$$Q_e = \frac{F}{U_e}\frac{(1-T_f)^N-1}{(-T_f(1-T_f)^N)} \quad (4)$$

The quantity of BMEs, the transition probability, annual funding, and average cost are needed. The number of bridge joints and their area is obtained by Chapter 6.2.1 in Table 10 and is described as all NBEs in relationship to BME joints. A percentage of 31.11% of joints are at-risk. Appendix 7 shows that this equals to 362,898ft^2 of bridge area and the area of joints (26,146 linear feet (lf)) can be found in the NBI element data. The transition probability (0.02) and average cost to repair joints (\$200/lf) are obtained by (Hearn 2015). For the annual funding different amounts are used for comparison. In this example, an annual funding of \$1,000,000/yr is used.

The number of years the preservation program needs to repair all bridge joints can now be calculated by transposing the Equation 4. Equation 5 then becomes:

$$N = \frac{\ln\frac{1{,}000{,}000}{1{,}000{,}000+26{,}146\text{lf}\times 0.02\times \$200/lf}}{\ln 1-0.02} = 4{,}92\ yrs \approx 5\ yrs \quad (5)$$

The program has to run 5 years to preserve all at-risk bridge joints, while bridges deteriorating into poor condition and thus are not eligible for preservation anymore.

With an annual funding of $1,000,000/yr and average costs of $200/lf for bridge joints, Equation 7 becomes:

$$(7) \qquad R_e = \frac{\$1{,}000{,}000}{\$200/_{lf}} = 5000\ lf$$

An amount of 5000 lf of bridge joints can be preserved with an annual funding of $1,000,000/yr. If the annual amount increases or decreases the amount of bridge joints that can be preserved will increases or decrease.

The amount of bridge deck area deteriorating into poor condition can then be calculated with the transposed Equation 8:

$$(8) \qquad D_e = 26{,}146ft^2 - 4{,}92yrs \times 5000\ \text{lf}$$

With this preservation program 24,600 lf of bridge joints would be preserved and 1,546 lf deteriorate to poor condition. The deck area lost to poor condition is 21,500 ft^2, as shown in Table 11.

Table 11: Program results

Annual Funding ($)	N (Years)	Porgram Expenditure	Joints Repaired (linear feet)	Deck Area to Poor Condition (square feet)	Total cost ($)
800.000	6,08	4.864.000	24.320	25.300	16.021.300
1.000.000	4,92	4.920.000	24.600	21.500	14.401.500
1.200.000	4,14	4.968.000	24.840	18.100	12.950.100

This table shows program results for different annual funding and amount of years the program needs to run. Program expenditures can be computed by using the number of years and annual funding, or the joints repaired and average cost for repairing joints. Percentages of joints not repaired in relation to all joints that need repair are used to calculate the deck area which deteriorates to poor condition, assuming the same percentage. The total costs are computed with the deck area deteriorated (ft^2) to poor condition and the average replacement unit cost ($\$/ft^2$) in Rhode Island (FHWA 2018e).

7. Conclusion

The purpose of this research was to gain valuable insight into the current state of preservation strategies. Each chapter of this study was intended to give a different aspect of how preservation is affecting the bridge life-cycle.

At first, the field bridge preservation and the history of BMSs are introduced. As it turns out, significant changes were made within the last years in case of rating and reporting of bridge conditions. A new threshold is applied and bridges are inspected on element-level.

Afterwards, deterioration as limiting factor for bridge lifespans is explored. Based on structure materials, special deterioration impacts were described. Contradicting, preservation expands the bridges lifespan. In conjunction with deterioration types different preservation aspects are examined. Terms are defined and preservation activities and outcomes presented as preliminary study for the methodology. Before the methodology of authoring preservation performance measures is described, cost aspects of preservation are presented and also used as valuable information.

The knowledge gained is combined by developing performance measures and applying in preservation programs, after the data is processed to display the current state of Rhode Island bridges. The performance measures for Rhode Island show 47,44% of bridges in a good preservation state and 27,29% at-risk to deteriorate to poor condition. The highest amounts of at-risk condition are shown for bridge joints, which implies a higher preservation need. That is why the preservation program for bridge joints is used to compute preservation needs, costs, as well as time and funding numbers. Different amounts can be applied to compute different outcomes. If Rhode

Island invests $1,200,000 annually in a bridge preservation program, 94% of bridge joints could be repaired within 4,92 years. With this annual funding just around 5% of the bridge deck area with bridge joints would deteriorate to poor condition during this program. The total cost would be $12,950,100; compared with $16,021,300 by investing only $800,000 annually; an advantage of $3,071,200. Not only the total cost is more preferable, the program would need to last 6,08 years to repair one percent less bridge joints and let around 7% of bridge deck area with bridge joints deteriorate during this time.

The numbers and conclusions presented implying that bridge preservation is needed and valuable. Rhode Island is the state with the highest number of structurally deficient bridges, but this is about to change. This study has given an overview on preservation strategies, performance measures, and programs. All the proposed methods could be applied for different datasets. The outcomes of this work can help state highway agencies to plan further action on bridge preservation nationwide.

Limitations

The given data set has a high potential for being utilized in future research. The scope of this particular research was to give an overview about the data and initial trends found within the dataset.

The first limitation to this work is that the data is limited and public. To better analyze the effectiveness of bridge preservation, data on cost of preservation activities, outcomes of preservation activities, and data on service intervals would be needed. With more data the results and conclusion could be more accurate. Future studies could include paper, reports and surveys from state highway agencies. Additionally, lists of completed repairs could be valuable information for performance measures.

The second limitation is the dataset itself. The NBI database seems to have discrepancies in bridge condition ratings due to unrecorded improvement works, or uncertainties in different data. Future studies could eliminate such discrepancies and uncertainties before authoring performance measure to analyze the given data more accurate.

Nevertheless, the results displayed are made with bridge element data, which is an important source of preservation measures. The bridges and bridge elements which need preservation can still be identified.

APPENDIX 1

Table 12: Preservation Activity Frequencies (WisDOT 2016)

Bridge Component	Bridge Preservation Type	Activity Description	Preventive Maintenance Type	Action Frequency (years)
All	Preventive Maintenance	Sweeping, power washing, cleaning	Cyclical	1-2
Deck	Preventive Maintenance	Deck washing	Cyclical	1
		Deck Sweeping		1
		Deck Sealing/Crack Sealing		4-5
		Thin polymer (Epoxy) overlays		10
		Drainage cleaning/repair		As needed
		Joint cleaning		
		Deck Patching	Condition Based	1- 2
		Chloride extraction		1 -2
		Asphalt overlay with membrane		12-15
		Polymer modified Asphalt overlay		6-12
		Joint seal replacement		10
		Drainage cleaning/repair		1
	Repair or Rehab Element	Rigid concrete overlays	Condition Based	As needed
		Structural Reinforced concrete overlay		
		Deck joint replacement		
		Eliminate joints		
Super	Preventive Maintenance	Bridge approach restoration	Cyclical	2
		Seat and beam ends washing		2
	Repair or Rehab Element	Bridge rail restoration	Condition Based	As needed
		Retrofit rail		
		Painting		
		Bearing restoration (replacement, cleaning, resetting)		
		Superstructure restoration		
		Pin and hanger replacement		
		Retrofit fracture critical members		
Sub	Preventive Maintenance	Substructure Restoration	Condition Based	As needed
		Scour Counter Measure		
		Channel Restoration		

APPENDIX 2

Table 13: Median Years for Condition States (Thompson, Paul D. 2017)

Element Group	Median Years from State 1 to State 2	Median Years from State 2 to State 3	Median Years from State 3 to State 4
A1 Concrete deck	6	48	51
A2 Concrete slab	4	47	25
A3 Prestressed concrete slab	5	79	50
A4 Steel deck	5	11	11
A5 Timber deck/slab	5	7	15
A6 Approach slabs	12	25	28
B1 Strip Seal expansion joint	13	23	23
B2 Pourable joint seal	10	4	4
B3 Compression joint seal	6	5	5
B4 Assembly joint/seal	14	7	7
B5 Open expansion joint	18	15	15
B6 Other expansion joint	19	30	30
C1 Uncoated metal rail	74	3	3
C2 Coated metal rail	18	10	4
C3 Reinforced concrete railing	68	24	38
C4 Timber railing	12	4	4
C5 Other railing	37	8	8
D1 Unpainted steel super/substructure	13	9	13
D2 Painted girder/floor beam/cable/pin and hanger	14	40	28
D3 Painted steel stringer	19	150	137
D4 Painted steel truss bottom	15	19	3
D5 Painted steel truss/arch top	10	90	76
D6 Prestressed concrete superstructure	293	16	11
D7 Reinforced concrete superstructure	32	16	15
D8 Timber superstructure	41	27	3
E1 Elastomeric bearings	96	121	121
E2 Metal bearings	14	24	24
F1 Painted steel substructure	12	9	2
F2 Prestressed column/pile/cap	16	40	62
F3 Reinforced concrete column/pile	41	46	84
F5 Reinforced concrete abutment	87	164	347
F6 Reinforced concrete cap	145	68	139
F7 Pile cap/footing	9	38	55
F8 Timber substructure	24	18	3
G1 Reinforced concrete culverts	7	37	138
G2 Metal and other culverts	8	29	34
H1 Channel	9	17	26
I1 Pile jacket w/o cathodic protection	13	17	18
I2 Pile jacket with cathodic protection	19	56	43
I3 Fender/dolphin/bulkhead/seawall	11	9	27
I4 Reinforced concrete slope protection	56	16	10
I5 Timber slope protection	62	17	82

APPENDIX 3

Table 14: Median Years for Condition States (Thompson, Paul D. 2017)

Element Group	Median Years from State 1 to State 2	Median Years from State 2 to State 3	Median Years from State 3 to State 4
I6 Other (incl. asphalt) slope protection	35	13	9
I7 Drainage system other materials	8	2	3
I7 Drainage system metal	8	3	1
J1 Uncoated metal wall	9	6	71
J2 Reinforced concrete wall	50	31	46
J3 Timber wall	24	9	8
J4 Other (incl. masonry) wall	10	18	19
J5 Mechanically stabilized earth wall	76	10	17
K1 Sign structures/hi-mast light poles	15	18	7
K1 Sign structures/hi-mast light poles (coated)	14	40	28
L1 Moveable bridge mechanical	12	34	12
L2 Moveable bridge brakes	5	7	6
L3 Moveable bridge motors	9	7	10
L4 Moveable bridge hydraulic power	8	15	13
L5 Moveable bridge pipe and conduit	6	14	14
L6 Moveable bridge structure	13	10	6
L7 Moveable bridge locks	4	6	15
L8 Moveable bridge live load items	6	11	11
L9 Moveable bridge counterweight/ trunnion/track	13	14	81
M1 Moveable bridge electronics	38	10	10
M2 Moveable bridge submarine cable	10	3	3
M3 Moveable bridge control console	9	8	8
M4 Moveable bridge navigational lights	9	5	5
M5 Moveable bridge operator facilities	14	19	19
M6 Moveable bridge misc. equipment	1	5	5
M7 Moveable bridge barriers/gates	10	10	10
M8 Moveable bridge traffic signals	30	3	3
P1 Deck wearing surface	12	57	36
P2 Paint on steel or stain on concrete	10	8	4
P3 Weathering steel patina	13	15	7
P4 Galvanized/metalized/other	8	46	17
P5 Reinforcing steel protective system	19	56	43

APPENDIX 4

Table 15: Bridges constructed, reconstructed, improved, last 10 years (Count)

Element to preserve	Element affecting exposure	Measure of Preservation	Last 10 years									Reference Number
			Constructed			Reconstructed			Imrpoved			
			Good	At Risk	Poor	Good	At Risk	Poor	Good	At Risk	Poor	
NBE	BME	NBE deck, superstructure, substructure, and culvert relative to BME, joints, coatings, and wearing surfaces	113	8	2	104	5	4	54	12	16	1
NBE deck	BME	NBE deck relative to BME joints, coatings, and wearing surfaces	112	8	0	100	5	0	61	16	2	2
NBE superstructure	BME	NBE superstructure relative to BME joints, coatings, and wearings surfaces	115	8	0	104	5	4	53	12	16	3
NBE substructure	BME	NBE substructure relative to BME joints, coatings, and wearing surfaces	113	8	2	108	5	0	62	16	3	4
NBE culvert	BME	NBE culvert relative to BME joints, coatings, and wearing surfaces	0	0	0	0	0	0	4	0	2	5
NBE concrete	BME	NBE concrete (continuous) deck, superstructure, substructure, and culvert relative to BME joints, coatings, and wearing surfaces	7	0	0	8	0	0	0	0	3	6
NBE prestressed concrete	BME	NBE prestressed concrete (continuous) deck, superstructure, substructure, and culvert relative to BME joints, coatings and wearing surfaces	30	3	2	20	1	4	13	1	5	7
NBE steel	BME	NBE steel (continuous) deck, superstructure, substructure, and culvert relative to BME joints, coatings, and wearing surfaces	76	4	0	76	4	0	40	11	8	8
NBE timber	BME	NBE timber deck, superstructure, substructure, and culvert relative to BME joints, coatings, and wearing surfaces	0	1	0	0	0	0	0	0	0	9
NBE Aluminium, Wrought Iron, Cast Iron	BME	NBE aluminium, wrought iron, and cast iron deck, superstructure, substructure, and culvert relative to BME joints, coatings, and wearing surfaces	0	0	0	0	0	0	0	0	0	10
NBE concrete	BME coating	Concrete (continuous) NBE relative to BME concrete coatings. Parent element IDs are enforced.	0	0	0	0	0	0	0	0	0	11
NBE steel	BME coating	Steel NBErelative to BME steel coatings. Parent element IDs are enforced.	46	1	0	30	2	0	19	6	4	12
NBE deck	BME wearing surface	NBE decks relative to BME wearing surfaces. Parent element IDs are enforced.	13	0	0	19	0	0	16	1	1	13
NBE	BME joint	NBE deck , superstructure, substructure, and culvert relative to BME joints	35	7	1	38	2	2	12	5	6	14
NBE deck	BME joint	NBE decks relative to joints	35	7	0	36	2	0	16	7	0	15
NBE superstructure	BME joint	NBE superstructure relative to BME joints	36	7	0	38	2	2	12	5	6	16
NBE substructure	BME joint	NBE substructure relative to BME joints	35	7	1	40	2	0	16	5	2	17
NBE concrete	BME joint	NBE concrete (continuous) deck, superstructure, substructure, and culvert relative to BME joints	3	0	0	3	0	0	0	0	1	18
NBE prestressed concrete	BME joint	NBE prestressed concrete (continuous) deck, superstructure, substructure, and culvert relative to BME joints	14	3	1	9	1	2	2	1	3	19
NBE steel	BME joint	NBE steel (continuous) deck, superstructure, substructure, and culvert relative to BME joints	18	3	0	26	1	0	10	4	2	20
NBE timber	BME joint	NBE timber deck, superstructure, substructure, and culvert relative to BME joints	0	1	0	0	0	0	0	0	0	21
NBE	BME joint, open	NBE deck , superstructure, substructure, and culvert relative to BME open joints	1	0	0	0	0	0	0	0	1	22
NBE	BME joint, other	NBE deck , superstructure, substructure, and culvert relative to BME other joints	9	1	0	16	0	1	5	2	0	23
NBE	BME joint, assembly without seal	NBE deck , superstructure, substructure, and culvert relative to BME assembly without seal joints	0	0	0	1	0	0	2	0	1	24
NBE	BME joint, assembly with seal (modular)	NBE deck, superstructure, substructure, and culvert relative to BME assembly with seal (modular) joints	2	1	0	1	1	0	0	1	0	25
NBE	BME joint, compression	NBE deck , superstructure, substructure, and culvert relative to BME compression joints	2	1	0	3	0	0	1	0	1	26
NBE	BME joint, strip seal	NBE deck , superstructure, substructure, and culvert relative to BME strip seal joints	7	2	0	3	0	0	0	1	0	27
NBE	BME joint, pourable	NBE deck , superstructure, substructure, and culvert relative to BME pourable joints	14	2	1	14	1	1	4	1	3	28

APPENDIX 5

Table 16: Performance measures with all bridges included

Element to preserve	Element affecting exposure	Measure of Preservation	Preservation performance (%)						Reference Number
			Area			Count			
			Good	At-risk	Poor	Good	At-risk	Poor	
NBE	BME	NBE deck, superstructure, substructure, and culvert relative to BME, joints, coatings, and wearing surfaces	49,77%	26,08%	24,15%	50,86%	21,02%	28,12%	1
NBE deck	BME	NBE deck relative to BME joints, coatings, and wearing surfaces	57,70%	35,21%	7,09%	61,69%	31,39%	6,92%	2
NBE superstructure	BME	NBE superstructure relative to BME joints, coatings, and wearings surfaces	54,13%	29,06%	16,80%	55,02%	24,37%	20,61%	3
NBE substructure	BME	NBE substructure relative to BME joints, coatings, and wearing surfaces	55,84%	31,01%	13,14%	59,69%	29,43%	10,88%	4
NBE culvert	BME	NBE culvert relative to BME joints, coatings, and wearing surfaces	97,06%	0,00%	2,94%	80,00%	0,00%	20,00%	5
NBE concrete	BME	NBE concrete (continuous) deck, superstructure, substructure, and culvert relative to BME joints, coatings, and wearing surfaces	55,48%	19,49%	25,02%	55,25%	14,36%	30,39%	6
NBE prestressed concrete	BME	NBE prestressed concrete (continuous) deck, superstructure, substructure, and culvert relative to BME joints, coatings and wearing surfaces	71,16%	18,71%	10,13%	63,21%	18,13%	18,65%	7
NBE steel	BME	NBE steel (continuous) deck, superstructure, substructure, and culvert relative to BME joints, coatings, and wearing surfaces	46,79%	27,30%	25,91%	48,33%	22,32%	29,35%	8
NBE timber	BME	NBE timber deck, superstructure, substructure, and culvert relative to BME joints, coatings, and wearing surfaces	74,27%	2,65%	23,07%	64,29%	7,14%	28,57%	9
NBE Aluminum, Wrought Iron, Cast Iron	BME	NBE aluminium, wrought iron, and cast iron deck, superstructure, substructure, and culvert relative to BME joints, coatings, and wearing surfaces	0,00%	0,00%	100,00%	0,00%	0,00%	100,00%	10
NBE concrete	BME coating	Concrete (continuous) NBE relative to BME concrete coatings. Parent element IDs are enforced.	82,49%	9,29%	8,22%	70,59%	17,65%	11,76%	11
NBE steel	BME coating	Steel NBErelative to BME steel coatings. Parent element IDs are enforced.	46,78%	31,58%	21,64%	45,10%	25,05%	29,85%	12
NBE deck	BME wearing surface	NBE decks relative to BME wearing surfaces. Parent element IDs are enforced.	78,88%	10,45%	10,67%	81,79%	10,26%	7,95%	13
NBE	BME joint	NBE deck , superstructure, substructure, and culvert relative to BME joints	43,35%	30,16%	26,49%	47,16%	26,42%	26,42%	14
NBE deck	BME joint	NBE decks relative to joints	51,91%	41,06%	7,03%	56,62%	37,27%	6,10%	15
NBE superstructure	BME joint	NBE superstructure relative to BME joints	49,11%	32,38%	18,51%	51,07%	29,58%	19,34%	16
NBE substructure	BME joint	NBE substructure relative to BME joints	49,82%	35,57%	14,61%	54,61%	35,02%	10,37%	17
NBE concrete	BME joint	NBE concrete (continuous) deck, superstructure, substructure, and culvert relative to BME joints	39,23%	34,01%	26,76%	44,90%	22,45%	32,65%	18
NBE prestressed concrete	BME joint	NBE prestressed concrete (continuous) deck, superstructure, substructure, and culvert relative to BME joints	53,43%	36,90%	9,67%	54,49%	30,34%	15,17%	19
NBE steel	BME joint	NBE steel (continuous) deck, superstructure, substructure, and culvert relative to BME joints	41,26%	28,53%	30,21%	44,80%	25,63%	29,57%	20
NBE timber	BME joint	NBE timber deck, superstructure, substructure, and culvert relative to BME joints	76,54%	5,66%	17,80%	66,67%	16,67%	16,67%	21
NBE	BME joint, open	NBE deck , superstructure, substructure, and culvert relative to BME open joints	38,26%	0,00%	61,74%	55,00%	0,00%	45,00%	22
NBE	BME joint, other	NBE deck , superstructure, substructure, and culvert relative to BME other joints	38,13%	22,15%	39,72%	54,75%	29,61%	15,64%	23
NBE	BME joint, assembly without seal	NBE deck , superstructure, substructure, and culvert relative to BME assembly without seal joints	63,84%	10,76%	25,41%	35,29%	14,71%	50,00%	24
NBE	BME joint, assembly with seal (modular)	NBE deck, superstructure, substructure, and culvert relative to BME assembly with seal (modular) joints	45,50%	46,53%	7,97%	52,63%	21,05%	26,32%	25
NBE	BME joint, compression	NBE deck , superstructure, substructure, and culvert relative to BME compression joints	33,54%	53,30%	13,16%	52,17%	27,54%	20,29%	26
NBE	BME joint, strip seal	NBE deck , superstructure, substructure, and culvert relative to BME strip seal joints	32,90%	47,52%	19,58%	58,06%	24,19%	17,74%	27
NBE	BME joint, pourable	NBE deck , superstructure, substructure, and culvert relative to BME pourable joints	43,30%	23,76%	32,94%	41,69%	29,30%	29,01%	28

APPENDIX 6

Table 17: Performance measures with all bridges included (Count)

Element to preserve	Element affecting exposure	Measure of Preservation	Preservation performance						Reference Number
			Good (count)	Good (%)	At-risk (coun	At-risk (%)	Poor (Count)	Poor (%)	
NBE	BME	NBE deck, superstructure, substructure, and culvert relative to BME, joints, coatings, and wearing surfaces	1.355	50,86%	560	21,02%	749	28,12%	1
NBE deck	BME	NBE deck relative to BME joints, coatings, and wearing surfaces	1.588	61,69%	808	31,39%	178	6,92%	2
NBE superstructure	BME	NBE superstructure relative to BME joints, coatings, and wearings surfaces	1.463	55,02%	648	24,37%	548	20,61%	3
NBE substructure	BME	NBE substructure relative to BME joints, coatings, and wearing surfaces	1.586	59,69%	782	29,43%	289	10,88%	4
NBE culvert	BME	NBE culvert relative to BME joints, coatings, and wearing surfaces	4	80,00%	0	0,00%	1	20,00%	5
NBE concrete	BME	NBE concrete (continuous) deck, superstructure, substructure, and culvert relative to BME joints, coatings, and wearing surfaces	100	55,25%	26	14,36%	55	30,39%	6
NBE prestressed concrete	BME	NBE prestressed concrete (continuous) deck, superstructure, substructure, and culvert relative to BME joints, coatings and wearing surfaces	244	63,21%	70	18,13%	72	18,65%	7
NBE steel	BME	NBE steel (continuous) deck, superstructure, substructure, and culvert relative to BME joints, coatings, and wearing surfaces	998	48,33%	461	22,32%	606	29,35%	8
NBE timber	BME	NBE timber deck, superstructure, substructure, and culvert relative to BME joints, coatings, and wearing surfaces	9	64,29%	1	7,14%	4	28,57%	9
NBE Aluminum, Wrought Iron, Cast Iron	BME	NBE aluminium, wrought iron, and cast iron deck, superstructure, substructure, and culvert relative to BME joints, coatings, and wearing surfaces	0	0,00%	0	0,00%	5	100,00%	10
NBE concrete	BME coating	Concrete (continuous) NBE relative to BME concrete coatings. Parent element IDs are enforced.	12	70,59%	3	17,65%	2	11,76%	11
NBE steel	BME coating	Steel NBErelative to BME steel coatings. Parent element IDs are enforced.	479	45,10%	266	25,05%	317	29,85%	12
NBE deck	BME wearing surface	NBE decks relative to BME wearing surfaces. Parent element IDs are enforced.	319	81,79%	40	10,26%	31	7,95%	13
NBE	BME joint	NBE deck , superstructure, substructure, and culvert relative to BME joints	373	47,16%	209	26,42%	209	26,42%	14
NBE deck	BME joint	NBE decks relative to joints	436	56,62%	287	37,27%	47	6,10%	15
NBE superstructure	BME joint	NBE superstructure relative to BME joints	404	51,07%	234	29,58%	153	19,34%	16
NBE substructure	BME joint	NBE substructure relative to BME joints	432	54,61%	277	35,02%	82	10,37%	17
NBE concrete	BME joint	NBE concrete (continuous) deck, superstructure, substructure, and culvert relative to BME joints	22	44,90%	11	22,45%	16	32,65%	18
NBE prestressed concrete	BME joint	NBE prestressed concrete (continuous) deck, superstructure, substructure, and culvert relative to BME joints	97	54,49%	54	30,34%	27	15,17%	19
NBE steel	BME joint	NBE steel (continuous) deck, superstructure, substructure, and culvert relative to BME	250	44,80%	143	25,63%	165	29,57%	20
NBE timber	BME joint	NBE timber deck, superstructure, substructure, and culvert relative to BME joints	4	66,67%	1	16,67%	1	16,67%	21
NBE	BME joint, open	NBE deck , superstructure, substructure, and culvert relative to BME open joints	11	55,00%	0	0,00%	9	45,00%	22
NBE	BME joint, other	NBE deck , superstructure, substructure, and culvert relative to BME other joints	98	54,75%	53	29,61%	28	15,64%	23
NBE	BME joint, assembly without seal	NBE deck , superstructure, substructure, and culvert relative to BME assembly without seal joints	24	35,29%	10	14,71%	34	50,00%	24
NBE	BME joint, assembly with seal (modular)	NBE deck, superstructure, substructure, and culvert relative to BME assembly with seal (modular) joints	20	52,63%	8	21,05%	10	26,32%	25
NBE	BME joint, compression	NBE deck , superstructure, substructure, and culvert relative to BME compression joints	36	52,17%	19	27,54%	14	20,29%	26
NBE	BME joint, strip seal	NBE deck , superstructure, substructure, and culvert relative to BME strip seal joints	36	58,06%	15	24,19%	11	17,74%	27
NBE	BME joint, pourable	NBE deck , superstructure, substructure, and culvert relative to BME pourable joints	148	41,69%	104	29,30%	103	29,01%	28

APPENDIX 7

Table 18: Performance measures with all bridges included (Area)

Element to preserve	Element affecting exposure	Measure of Preservation	Preservation performance						Reference Number
			Good (Area)	Good (%)	At-risk (Area	At-risk (%)	Poor (Area)	Poor (%)	
NBE	BME	NBE deck, superstructure, substructure, and culvert relative to BME, joints, coatings, and wearing surfaces	2.077.178	49,77%	1.088.436	26,08%	1.008.114	24,15%	1
NBE deck	BME	NBE deck relative to BME joints, coatings, and wearing surfaces	2.390.456	57,70%	1.458.729	35,21%	293.708	7,09%	2
NBE superstructure	BME	NBE superstructure relative to BME joints, coatings, and wearings surfaces	2.256.803	54,13%	1.211.724	29,06%	700.512	16,80%	3
NBE substructure	BME	NBE substructure relative to BME joints, coatings, and wearing surfaces	2.328.062	55,84%	1.292.973	31,01%	547.873	13,14%	4
NBE culvert	BME	NBE culvert relative to BME joints, coatings, and wearing surfaces	4.492	97,06%	0	0,00%	136	2,94%	5
NBE concrete	BME	NBE concrete (continuous) deck, superstructure, substructure, and culvert relative to BME joints, coatings, and wearing surfaces	65.520	55,48%	23.018	19,49%	29.550	25,02%	6
NBE prestressed concrete	BME	NBE prestressed concrete (continuous) deck, superstructure, substructure, and culvert relative to BME joints, coatings and wearing surfaces	331.669	71,16%	87.193	18,71%	47.198	10,13%	7
NBE steel	BME	NBE steel (continuous) deck, superstructure, substructure, and culvert relative to BME joints, coatings, and wearing surfaces	1.675.906	46,79%	977.756	27,30%	928.113	25,91%	8
NBE timber	BME	NBE timber deck, superstructure, substructure, and culvert relative to BME joints, coatings, and wearing surfaces	1.386	74,27%	49	2,65%	430	23,07%	9
NBE Aluminum, Wrought Iron, Cast Iron	BME	NBE aluminium, wrought iron, and cast iron deck, superstructure, substructure, and culvert relative to BME joints, coatings, and wearing surfaces	0	0,00%	0	0,00%	1.114	100,00%	10
NBE concrete	BME coating	Concrete (continuous) NBE relative to BME concrete coatings. Parent element IDs are enforced.	8.073	82,49%	909	9,29%	804	8,22%	11
NBE steel	BME coating	Steel NBErelative to BME steel coatings. Parent element IDs are enforced.	986.185	46,78%	665.638	31,58%	456.160	21,64%	12
NBE deck	BME wearing surface	NBE decks relative to BME wearing surfaces. Parent element IDs are enforced.	384.667	78,88%	50.953	10,45%	52.026	10,67%	13
NBE	BME joint	NBE deck , superstructure, substructure, and culvert relative to BME joints	521.712	43,35%	362.898	30,16%	318.787	26,49%	14
NBE deck	BME joint	NBE decks relative to joints	620.639	51,91%	490.917	41,06%	83.996	7,03%	15
NBE superstructure	BME joint	NBE superstructure relative to BME joints	590.933	49,11%	389.700	32,38%	222.764	18,51%	16
NBE substructure	BME joint	NBE substructure relative to BME joints	599.494	49,82%	428.037	35,57%	175.867	14,61%	17
NBE concrete	BME joint	NBE concrete (continuous) deck, superstructure, substructure, and culvert relative to BME joints	15.200	39,23%	13.177	34,01%	10.367	26,76%	18
NBE prestressed concrete	BME joint	NBE prestressed concrete (continuous) deck, superstructure, substructure, and culvert relative to BME joints	112.587	53,43%	77.765	36,90%	20.385	9,67%	19
NBE steel	BME joint	NBE steel (continuous) deck, superstructure, substructure, and culvert relative to BME joints	393.256	41,26%	271.907	28,53%	287.879	30,21%	20
NBE timber	BME joint	NBE timber deck, superstructure, substructure, and culvert relative to BME joints	669	76,54%	49	5,66%	156	17,80%	21
NBE	BME joint, open	NBE deck , superstructure, substructure, and culvert relative to BME open joints	8.102	38,26%	0	0,00%	13.072	61,74%	22
NBE	BME joint, other	NBE deck , superstructure, substructure, and culvert relative to BME other joints	91.825	38,13%	53.356	22,15%	95.653	39,72%	23
NBE	BME joint, assembly without seal	NBE deck , superstructure, substructure, and culvert relative to BME assembly without seal joints	128.306	63,84%	21.623	10,76%	51.062	25,41%	24
NBE	BME joint, assembly with seal (modular)	NBE deck, superstructure, substructure, and culvert relative to BME assembly with seal (modular) joints	66.265	45,50%	67.763	46,53%	11.613	7,97%	25
NBE	BME joint, compression	NBE deck , superstructure, substructure, and culvert relative to BME compression joints	44.508	33,54%	70.733	53,30%	17.470	13,16%	26
NBE	BME joint, strip seal	NBE deck , superstructure, substructure, and culvert relative to BME strip seal joints	54.854	32,90%	79.248	47,52%	32.653	19,58%	27
NBE	BME joint, pourable	NBE deck , superstructure, substructure, and culvert relative to BME pourable joints	127.851	43,30%	70.175	23,76%	97.264	32,94%	28

APPENDIX 8

Table 19: Preservation performance subtracted bridges (Count)

Element to preserve	Element affecting exposure	Measure of Preservation	Preservation performance						Reference Number
			Good (count)	Good (%)	At-risk (count)	At-risk (%)	Poor (Count)	Poor (%)	
NBE	BME	NBE deck, superstructure, substructure, and culvert relative to BME, joints, coatings, and wearing surfaces	1.242	48,69%	560	21,95%	749	29,36%	1
NBE deck	BME	NBE deck relative to BME joints, coatings, and wearing surfaces	1.476	59,40%	831	33,44%	178	7,16%	2
NBE superstructure	BME	NBE superstructure relative to BME joints, coatings, and wearings surfaces	1.348	52,97%	649	25,50%	548	21,53%	3
NBE substructure	BME	NBE substructure relative to BME joints, coatings, and wearing surfaces	1.473	57,88%	783	30,77%	289	11,36%	4
NBE culvert	BME	NBE culvert relative to BME joints, coatings, and wearing surfaces	4	80,00%	0	0,00%	1	20,00%	5
NBE concrete	BME	NBE concrete (continuous) deck, superstructure, substructure, and culvert relative to BME joints, coatings, and wearing surfaces	93	53,45%	26	14,94%	55	31,61%	6
NBE prestressed concrete	BME	NBE prestressed concrete (continuous) deck, superstructure, substructure, and culvert relative to BME joints, coatings and wearing surfaces	214	60,11%	70	19,66%	72	20,22%	7
NBE steel	BME	NBE steel (continuous) deck, superstructure, substructure, and culvert relative to BME joints, coatings, and wearing surfaces	922	46,35%	461	23,18%	606	30,47%	8
NBE timber	BME	NBE timber deck, superstructure, substructure, and culvert relative to BME joints, coatings, and wearing surfaces	9	64,29%	1	7,14%	4	28,57%	9
NBE Aluminum, Wrought Iron, Cast Iron	BME	NBE aluminium, wrought iron, and cast iron deck, superstructure, substructure, and culvert relative to BME joints, coatings, and wearing surfaces	0	0,00%	0	0,00%	5	100,00%	10
NBE concrete	BME coating	Concrete (continuous) NBE relative to BME concrete coatings. Parent element IDs are enforced.	12	70,59%	3	17,65%	2	11,76%	11
NBE steel	BME coating	Steel NBErelative to BME steel coatings. Parent element IDs are enforced.	433	42,62%	266	26,18%	317	31,20%	12
NBE deck	BME wearing surface	NBE decks relative to BME wearing surfaces. Parent element IDs are enforced.	306	81,17%	40	10,61%	31	8,22%	13
NBE	BME joint	NBE deck , superstructure, substructure, and culvert relative to BME joints	338	44,71%	209	27,65%	209	27,65%	14
NBE deck	BME joint	NBE decks relative to joints	401	53,90%	296	39,78%	47	6,32%	15
NBE superstructure	BME joint	NBE superstructure relative to BME joints	368	48,74%	234	30,99%	153	20,26%	16
NBE substructure	BME joint	NBE substructure relative to BME joints	397	52,51%	277	36,64%	82	10,85%	17
NBE concrete	BME joint	NBE concrete (continuous) deck, superstructure, substructure, and culvert relative to BME joints	19	41,30%	11	23,91%	16	34,78%	18
NBE prestressed concrete	BME joint	NBE prestressed concrete (continuous) deck, superstructure, substructure, and culvert relative to BME joints	83	50,61%	54	32,93%	27	16,46%	19
NBE steel	BME joint	NBE steel (continuous) deck, superstructure, substructure, and culvert relative to BME joints	232	42,96%	143	26,48%	165	30,56%	20
NBE timber	BME joint	NBE timber deck, superstructure, substructure, and culvert relative to BME joints	4	66,67%	1	16,67%	1	16,67%	21
NBE	BME joint, open	NBE deck , superstructure, substructure, and culvert relative to BME open joints	10	52,63%	0	0,00%	9	47,37%	22
NBE	BME joint, other	NBE deck , superstructure, substructure, and culvert relative to BME other joints	89	52,35%	53	31,18%	28	16,47%	23
NBE	BME joint, assembly without seal	NBE deck , superstructure, substructure, and culvert relative to BME assembly without seal joints	24	35,29%	10	14,71%	34	50,00%	24
NBE	BME joint, assembly with seal (modular)	NBE deck, superstructure, substructure, and culvert relative to BME assembly with seal (modular) joints	18	50,00%	8	22,22%	10	27,78%	25
NBE	BME joint, compression	NBE deck , superstructure, substructure, and culvert relative to BME compression joints	34	50,75%	19	28,36%	14	20,90%	26
NBE	BME joint, strip seal	NBE deck , superstructure, substructure, and culvert relative to BME strip seal joints	29	52,73%	15	27,27%	11	20,00%	27
NBE	BME joint, pourable	NBE deck , superstructure, substructure, and culvert relative to BME pourable joints	134	39,30%	104	30,50%	103	30,21%	28

APPENDIX 9

Table 20: Preservation performance subtracted bridges (Area)

Element to preserve	Element affecting exposure	Measure of Preservation	Preservation performance						Reference Number
			Good (Area)	Good (%)	At-risk (Area)	At-risk (%)	Poor (Area)	Poor (%)	
NBE	BME	NBE deck, superstructure, substructure, and culvert relative to BME, joints, coatings, and wearing surfaces	1.892.569	47,44%	1.088.436	27,29%	1.008.114	25,27%	1
NBE deck	BME	NBE deck relative to BME joints, coatings, and wearing surfaces	2.206.238	55,73%	1.458.729	36,85%	293.708	7,42%	2
NBE superstructure	BME	NBE superstructure relative to BME joints, coatings, and wearings surfaces	2.071.981	52,00%	1.211.724	30,41%	700.512	17,58%	3
NBE substructure	BME	NBE substructure relative to BME joints, coatings, and wearing surfaces	2.143.453	53,80%	1.292.973	32,45%	547.873	13,75%	4
NBE culvert	BME	NBE culvert relative to BME joints, coatings, and wearing surfaces	4.492	97,06%	0	0,00%	136	2,94%	5
NBE concrete	BME	NBE concrete (continuous) deck, superstructure, substructure, and culvert relative to BME joints, coatings, and wearing surfaces	61.425	53,88%	23.018	20,19%	29.550	25,92%	6
NBE prestressed concrete	BME	NBE prestressed concrete (continuous) deck, superstructure, substructure, and culvert relative to BME joints, coatings and wearing surfaces	315.582	70,13%	87.193	19,38%	47.198	10,49%	7
NBE steel	BME	NBE steel (continuous) deck, superstructure, substructure, and culvert relative to BME joints, coatings, and wearing surfaces	1.511.480	44,23%	977.756	28,61%	928.113	27,16%	8
NBE timber	BME	NBE timber deck, superstructure, substructure, and culvert relative to BME joints, coatings, and wearing surfaces	1.386	74,27%	49	2,65%	430	23,07%	9
NBE Aluminum, Wrought Iron, Cast Iron	BME	NBE aluminium, wrought iron, and cast iron deck, superstructure, substructure, and culvert relative to BME joints, coatings, and wearing surfaces	0	0,00%	0	0,00%	1.114	100,00%	10
NBE concrete	BME coating	Concrete (continuous) NBE relative to BME concrete coatings. Parent element IDs are enforced.	8.073	82,49%	909	9,29%	804	8,22%	11
NBE steel	BME coating	Steel NBErelative to BME steel coatings. Parent element IDs are enforced.	879.538	43,95%	665.638	33,26%	456.160	22,79%	12
NBE deck	BME wearing surface	NBE decks relative to BME wearing surfaces. Parent element IDs are enforced.	353.690	77,45%	50.953	11,16%	52.026	11,39%	13
NBE	BME joint	NBE deck , superstructure, substructure, and culvert relative to BME joints	484.900	41,57%	362.898	31,11%	318.787	27,33%	14
NBE deck	BME joint	NBE decks relative to joints	583.922	50,39%	490.917	42,36%	83.996	7,25%	15
NBE superstructure	BME joint	NBE superstructure relative to BME joints	554.015	47,49%	389.700	33,41%	222.764	19,10%	16
NBE substructure	BME joint	NBE substructure relative to BME joints	562.682	48,23%	428.037	36,69%	175.867	15,08%	17
NBE concrete	BME joint	NBE concrete (continuous) deck, superstructure, substructure, and culvert relative to BME joints	13.218	35,96%	13.177	35,84%	10.367	28,20%	18
NBE prestressed concrete	BME joint	NBE prestressed concrete (continuous) deck, superstructure, substructure, and culvert relative to BME joints	103.699	51,37%	77.765	38,53%	20.385	10,10%	19
NBE steel	BME joint	NBE steel (continuous) deck, superstructure, substructure, and culvert relative to BME joints	367.314	39,62%	271.907	29,33%	287.879	31,05%	20
NBE timber	BME joint	NBE timber deck, superstructure, substructure, and culvert relative to BME joints	669	76,54%	49	5,66%	156	17,80%	21
NBE	BME joint, open	NBE deck , superstructure, substructure, and culvert relative to BME open joints	7.971	37,88%	0	0,00%	13.072	62,12%	22
NBE	BME joint, other	NBE deck , superstructure, substructure, and culvert relative to BME other joints	87.230	36,92%	53.356	22,59%	95.653	40,49%	23
NBE	BME joint, assembly without seal	NBE deck , superstructure, substructure, and culvert relative to BME assembly without seal joints	128.306	63,84%	21.623	10,76%	51.062	25,41%	24
NBE	BME joint, assembly with seal (modular)	NBE deck, superstructure, substructure, and culvert relative to BME assembly with seal (modular) joints	52.449	39,79%	67.763	51,40%	11.613	8,81%	25
NBE	BME joint, compression	NBE deck , superstructure, substructure, and culvert relative to BME compression joints	42.550	32,54%	70.733	54,10%	17.470	13,36%	26
NBE	BME joint, strip seal	NBE deck , superstructure, substructure, and culvert relative to BME strip seal joints	46.613	29,41%	79.248	49,99%	32.653	20,60%	27
NBE	BME joint, pourable	NBE deck , superstructure, substructure, and culvert relative to BME pourable joints	119.782	41,70%	70.175	24,43%	97.264	33,86%	28

APPENDIX 10

Table 21: Preservation performance with all bridges included

Element to preserve	Element affecting exposure	Measure of Preservation	Preservation performance (%)						Reference Number
			Area			Count			
			Good	At-risk	Poor	Good	At-risk	Poor	
NBE	BME	NBE deck, superstructure, substructure, and culvert relative to BME, joints, coatings, and wearing surfaces	49,77%	26,08%	24,15%	50,86%	21,02%	28,12%	1
NBE deck	BME	NBE deck relative to BME joints, coatings, and wearing surfaces	57,70%	35,21%	7,09%	61,69%	31,39%	6,92%	2
NBE superstructure	BME	NBE superstructure relative to BME joints, coatings, and wearings surfaces	54,13%	29,06%	16,80%	55,02%	24,37%	20,61%	3
NBE substructure	BME	NBE substructure relative to BME joints, coatings, and wearing surfaces	55,84%	31,01%	13,14%	59,69%	29,43%	10,88%	4
NBE culvert	BME	NBE culvert relative to BME joints, coatings, and wearing surfaces	97,06%	0,00%	2,94%	80,00%	0,00%	20,00%	5
NBE concrete	BME	NBE concrete (continuous) deck, superstructure, substructure, and culvert relative to BME joints, coatings, and wearing surfaces	55,48%	19,49%	25,02%	55,25%	14,36%	30,39%	6
NBE prestressed concrete	BME	NBE prestressed concrete (continuous) deck, superstructure, substructure, and culvert relative to BME joints, coatings and wearing surfaces	71,16%	18,71%	10,13%	63,21%	18,13%	18,65%	7
NBE steel	BME	NBE steel (continuous) deck, superstructure, substructure, and culvert relative to BME joints, coatings, and wearing surfaces	46,79%	27,30%	25,91%	48,33%	22,32%	29,35%	8
NBE timber	BME	NBE timber deck, superstructure, substructure, and culvert relative to BME joints, coatings, and wearing surfaces	74,27%	2,65%	23,07%	64,29%	7,14%	28,57%	9
NBE Aluminum, Wrought Iron, Cast Iron	BME	NBE aluminium, wrought iron, and cast iron deck, superstructure, substructure, and culvert relative to BME joints, coatings, and wearing surfaces	0,00%	0,00%	100,00%	0,00%	0,00%	100,00%	10
NBE concrete	BME coating	Concrete (continuous) NBE relative to BME concrete coatings. Parent element IDs are enforced.	82,49%	9,29%	8,22%	70,59%	17,65%	11,76%	11
NBE steel	BME coating	Steel NBErelative to BME steel coatings. Parent element IDs are enforced.	46,78%	31,58%	21,64%	45,10%	25,05%	29,85%	12
NBE deck	BME wearing surface	NBE decks relative to BME wearing surfaces. Parent element IDs are enforced.	78,88%	10,45%	10,67%	81,79%	10,26%	7,95%	13
NBE	BME joint	NBE deck , superstructure, substructure, and culvert relative to BME joints	43,35%	30,16%	26,49%	47,16%	26,42%	26,42%	14
NBE deck	BME joint	NBE decks relative to joints	51,91%	41,06%	7,03%	56,62%	37,27%	6,10%	15
NBE superstructure	BME joint	NBE superstructure relative to BME joints	49,11%	32,38%	18,51%	51,07%	29,58%	19,34%	16
NBE substructure	BME joint	NBE substructure relative to BME joints	49,82%	35,57%	14,61%	54,61%	35,02%	10,37%	17
NBE concrete	BME joint	NBE concrete (continuous) deck, superstructure, substructure, and culvert relative to BME joints	39,23%	34,01%	26,76%	44,90%	22,45%	32,65%	18
NBE prestressed concrete	BME joint	NBE prestressed concrete (continuous) deck, superstructure, substructure, and culvert relative to BME joints	53,43%	36,90%	9,67%	54,49%	30,34%	15,17%	19
NBE steel	BME joint	NBE steel (continuous) deck, superstructure, substructure, and culvert relative to BME joints	41,26%	28,53%	30,21%	44,80%	25,63%	29,57%	20
NBE timber	BME joint	NBE timber deck, superstructure, substructure, and culvert relative to BME joints	76,54%	5,66%	17,80%	66,67%	16,67%	16,67%	21
NBE	BME joint, open	NBE deck , superstructure, substructure, and culvert relative to BME open joints	38,26%	0,00%	61,74%	55,00%	0,00%	45,00%	22
NBE	BME joint, other	NBE deck , superstructure, substructure, and culvert relative to BME other joints	38,13%	22,15%	39,72%	54,75%	29,61%	15,64%	23
NBE	BME joint, assembly without seal	NBE deck , superstructure, substructure, and culvert relative to BME assembly without seal joints	63,84%	10,76%	25,41%	35,29%	14,71%	50,00%	24
NBE	BME joint, assembly with seal (modular)	NBE deck, superstructure, substructure, and culvert relative to BME assembly with seal (modular) joints	45,50%	46,53%	7,97%	52,63%	21,05%	26,32%	25
NBE	BME joint, compression	NBE deck , superstructure, substructure, and culvert relative to BME compression joints	33,54%	53,30%	13,16%	52,17%	27,54%	20,29%	26
NBE	BME joint, strip seal	NBE deck , superstructure, substructure, and culvert relative to BME strip seal joints	32,90%	47,52%	19,58%	58,06%	24,19%	17,74%	27
NBE	BME joint, pourable	NBE deck , superstructure, substructure, and culvert relative to BME pourable joints	43,30%	23,76%	32,94%	41,69%	29,30%	29,01%	28

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