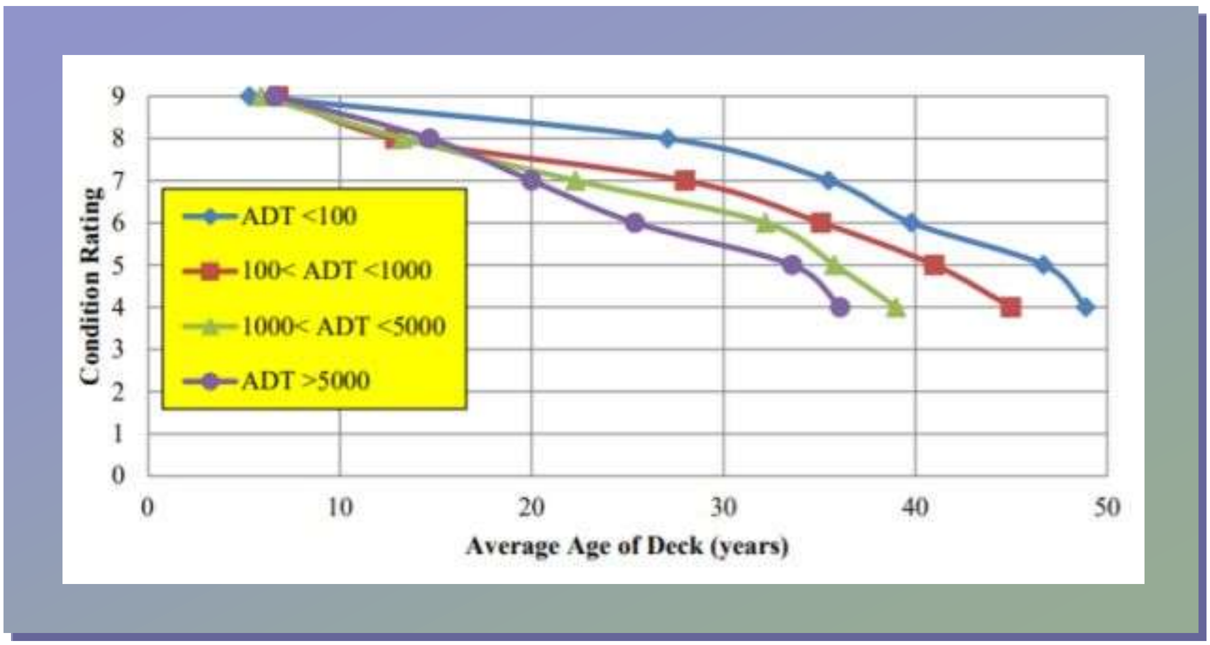
New Hampshire DOT

Research



Using Data Analytics in Forecasting Future Bridge Conditions

Final Report

Prepared by the University of New Hampshire Department of Civil and Environmental Engineering
for the New Hampshire Department of Transportation, in cooperation with the
U.S. Department of Transportation, Federal Highway Administration

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16. Abstract

Reliable data-driven forecasting models allow for public agencies to plan for future needs and resource allocation. Conditions of bridge assets are managed through maintenance, preservation, rehabilitation and reconstruction. The New Hampshire Department of Transportation documents the appropriate timing of these treatments in Recommended Investment Schedules (RIS). Adhering to a bridge’s RIS extends useful service life. Quantification of the service life extension as well as how well bridges have adhered to Recommended Investment Schedules remains a challenge.

Element-level condition assessment data is collected and tracked in a standardized format for each bridge asset in a transportation network. Maintenance and repair records, however, are not and must be tabulated before correlation with other data. Correlating this tabulated data with conditions will support the development of deterioration models that function according to treatment actions, environmental condition, and traffic usage. Condition forecasting using such deterioration models will provide insight into the long-term ramifications of investment strategies that leverage varying amount of maintenance, preservation, and rehabilitation.

This research presents an approach to development of a framework to track adherence to recommended bridge investment strategies. Preliminary bridge condition processing and literature reviews of relevant deterioration modeling are included.

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Using Data Analytics in Forecasting Bridge Condition

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DISCLAIMER

Using Data Analytics in Forecasting Bridge Condition

Final Project Report

NHDOT Project #SPR 26962V

July 2021

Executive Summary

Due to restrictions on in-person activities and access to NHDOT facilities and records due to the COVID-19 pandemic, several of the project tasks related to Grant #13T105, Using Data Analytics in Forecast Bridge Condition (SPR2 26962V) were not possible. Additionally, recent activities including FHWA training has altered the end goals of this project. Through no fault of the UNH or NHDOT personnel involved in this project, both parties agree that it is appropriate to terminate this project on June 30, 2021, with the completion of the literature surveys and preliminary bridge condition data processing. These deliverables are submitted in this report and attachments.

Reliable data-driven forecasting models allow for public agencies to plan for future needs and resource allocation. Conditions of bridge assets are managed through maintenance, preservation, rehabilitation, and reconstruction. The New Hampshire Department of Transportation documents the appropriate timing of these treatments in Recommended Investment Strategies (RIS). According to NHDOT best practice and expert judgement, adhering to a bridge's RIS extends useful service life. Quantification of the service life extension as well as tracking how well bridge investments have adhered to RIS remains a challenge. Bridge work is often documented in disparate formats through multiple bureaus and systems.

Element-level condition assessment data is collected and tracked in a standardized format for each bridge asset in a transportation network. Maintenance and repair records, however, are not and must be tabulated before correlation with other data. Correlating this tabulated data with conditions will support the development of deterioration models that function according to treatment actions, environmental condition, and traffic usage. Condition forecasting using such deterioration models will provide insight into the long-term ramifications of investment strategies that leverage varying amount of maintenance, preservation, and rehabilitation.

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Using Data Analytics in Forecasting Bridge Condition: Project Outline

Project Period (revised)

07/31/2019 – 06/30/2021

Project Team

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- Sebastian Young, UNH Graduate Student
- Sumit Purkayastha, UNH Graduate Student

Objectives (revised)

1. Data summary and RIS adherence recommendations
2. Deterioration modeling research synthesis

Project Scope (revised)

1. Process available bridge data and potential RIS adherence sample dataset.
2. Design expert judgement survey for RIS adherence factors.
3. Complete literature survey of relevant department of transportation deterioration modeling research.

Bridge Data Summary

New Hampshire DOT bridge data was collected and explored as one step in the development of a tool to measure Recommended Investment Strategy (RIS) adherence. Due to COVID-19 impacts discussed in the executive summary, the tool was not completed but an initial merger and summary of the data was completed, as presented in this report.

There are mainly 5 types of bridges in the RIS, which have separate maintenance, preservation, and rehabilitation measures: Girder, Culvert, Truss, Timber, Moveable. Based on these varying RIS strategies, the categories will have separate condition deterioration patterns of their elements. Categorizing the bridges using these categories will help to build an RIS adherence tool. However, the analysis for this project focused only on the "Girder" bridge category.

One of the primary goals of analyzing girder bridge data was to select a sample data set that could be used for the RIS adherence procedure development and testing. Using UNH team expertise and DOT preferences, the data is categorized by main bridge characteristics of interest, Tier, Location, Age, and Condition. To better demonstrate the distribution of girder bridges in the network and select a sample dataset in future projects, histograms are shown below in Figure 1 and Figure 2. The terms F, G, and P are used to group bridges into condition categories according to definitions from the NHDOT Bridge Program. F = Fair = "Red" = NBIS rating of 5 or 6. G = Good = "Green" = NBIS rating equal to or greater than 7. P = Poor = "Red" = NBIS rating of 4 or less.

The following data comprises 2,003 Girder bridges, which includes State non-Turnpike, State Turnpike, and Municipal or Other ownership, seen in Appendix A (NHDOT Bridge Program Recommended Investment Strategy from 2018).

Figure 1 shows the distribution of bridges with each condition rating by average age, separated by classification and location. Figure 1 summarizes the data and shows how these bridge characteristics vary by condition rating, which is the main outcome of interest for deterioration modeling and RIS adherence. For example, Figure 1 shows that the average number of bridges in the "Good" condition rating is the greatest in Tier 1, in the Bridge age of 10-50 years, in Grafton and Rockingham counties. Conversely, the graph shows the low number of older bridges (70+ years) in the "Good" condition rating. Figure 2 displays the same data with more granularity in age data.

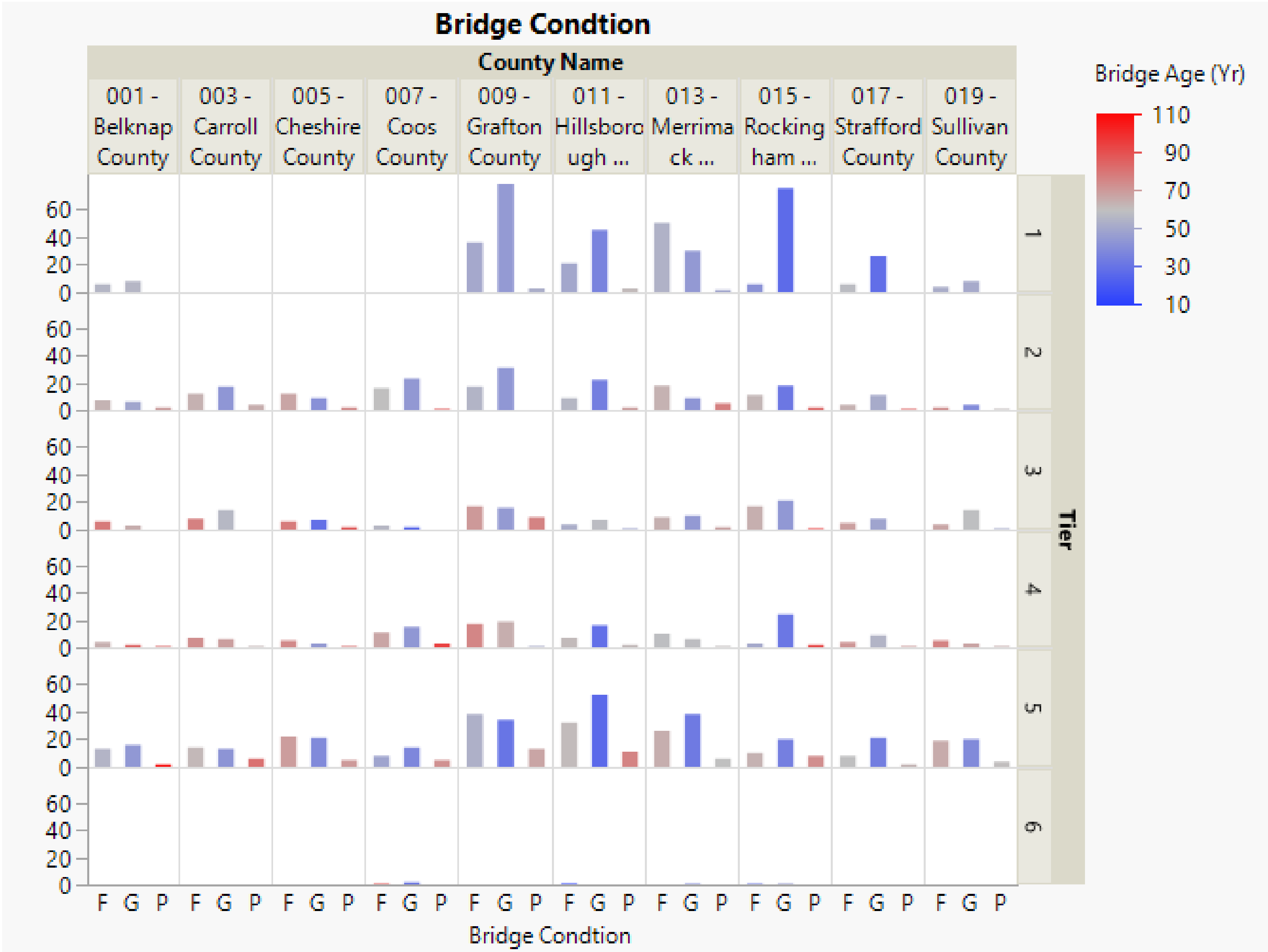

Figure 1: Bridge Count per Condition by County and Average Age

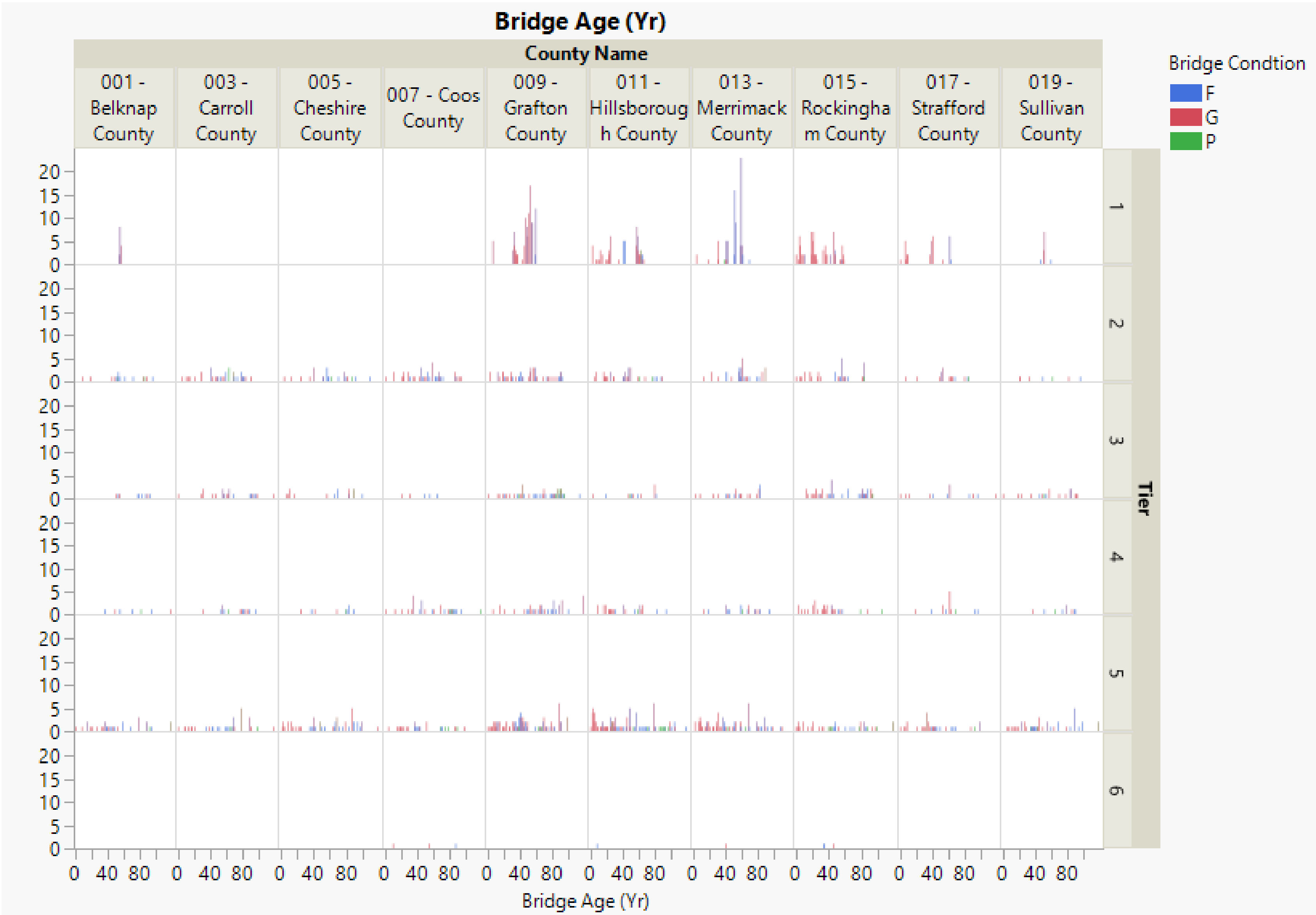

Figure 2: Bridge Distribution by Condition, County, and Age

Previous research highlights the role of location (i.e., counties) in bridge condition (Hatami and Morcous, 2011). As the traffic volume and traffic behavior change with different locations, the condition deterioration pattern also changes. Figure 3 shows the number of bridges in each condition rating by county.

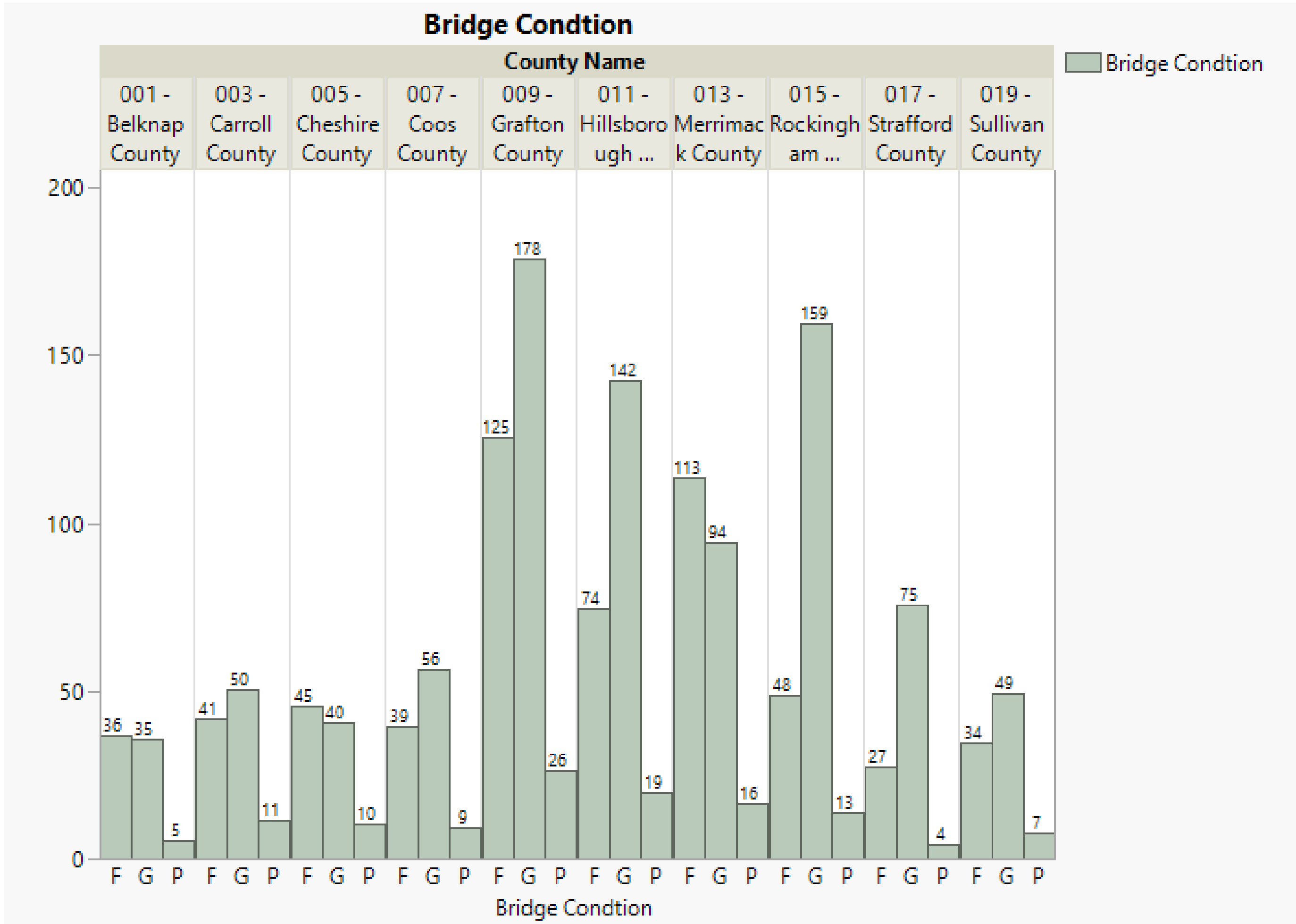

Figure 3: Bridge Count per Condition by County

Figure 4 shows similar histograms separated by both county and NHDOT Tier classification. A representative sample could be selected from all tiers or from a subset of tiers, depending on NHDOT interests and goals of future research.

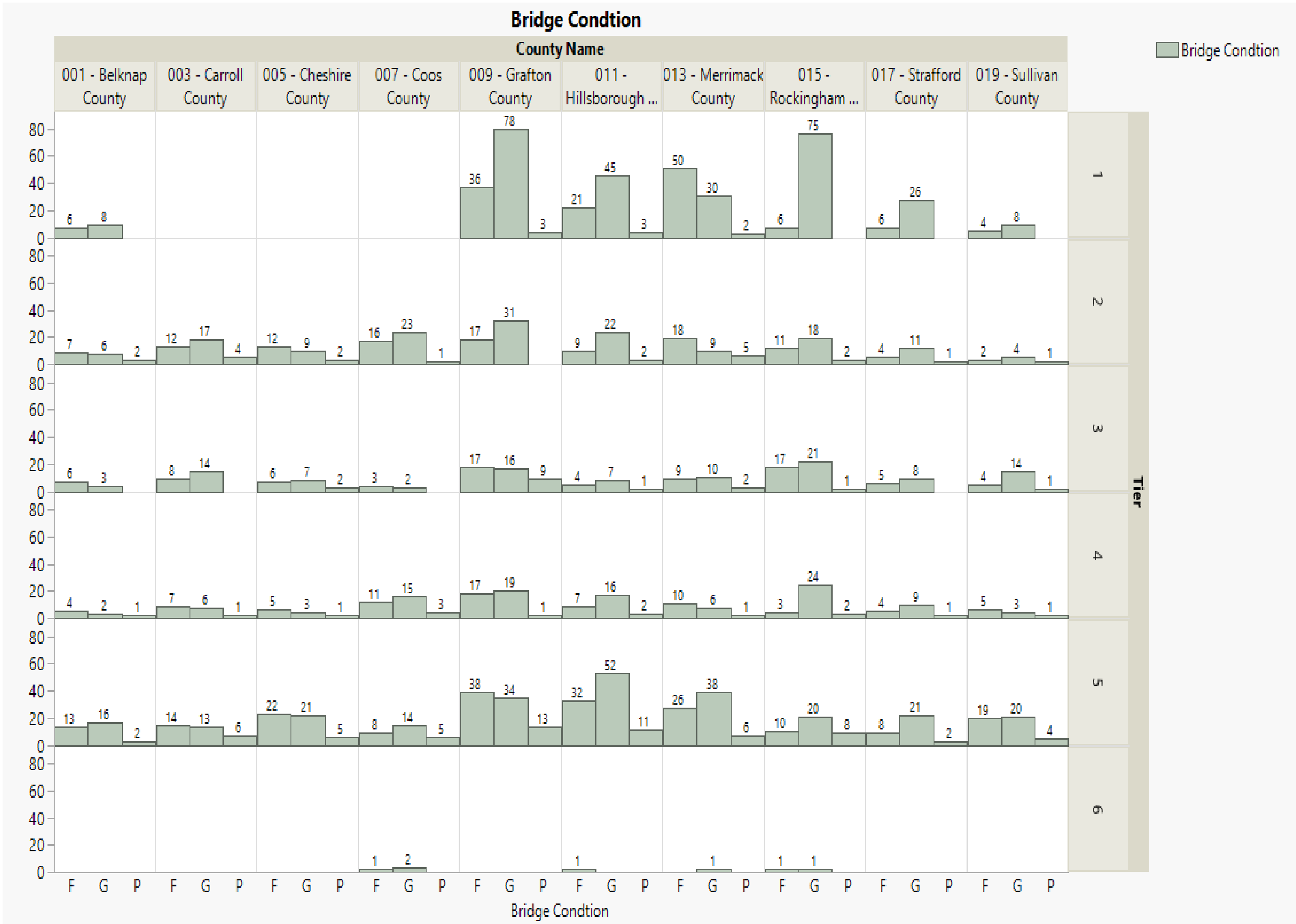

Figure 4: Bridge Count per Condition by Tier and County

To better understand the total distribution of bridges by counties, Figure 5 simply shows the total number of bridges in each condition rating by county. Here, most of the "Good" bridges are in the Grafton County, Hillsborough, Merrimack, and Rockingham County.

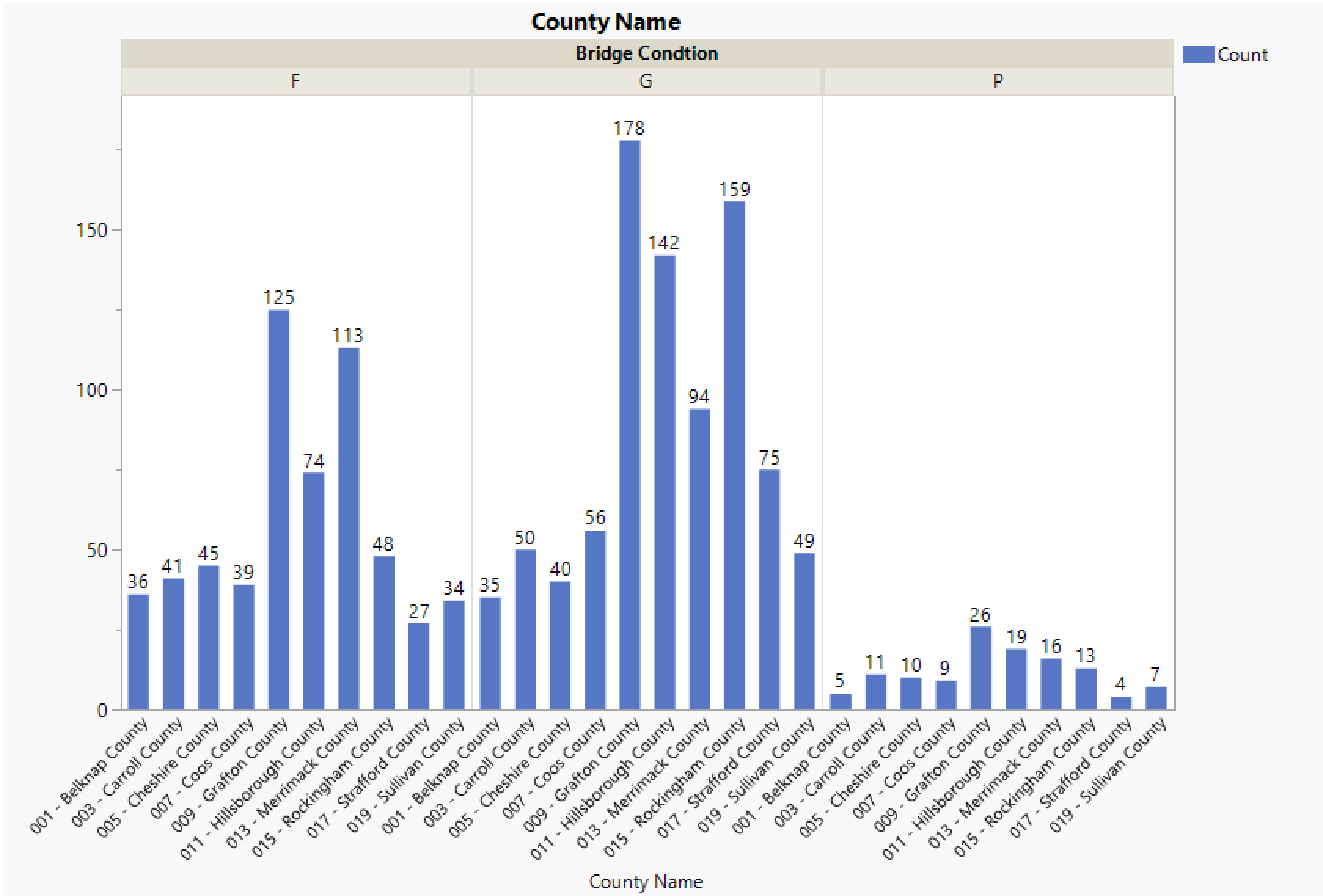

Figure 5: Bridge Count per Condition Rating by County

Figure 6 shows a summary of bridge count by age (grouped in 10-year increments) within each condition rating and Figure 7 shows a more detailed distribution by individual bridge age.

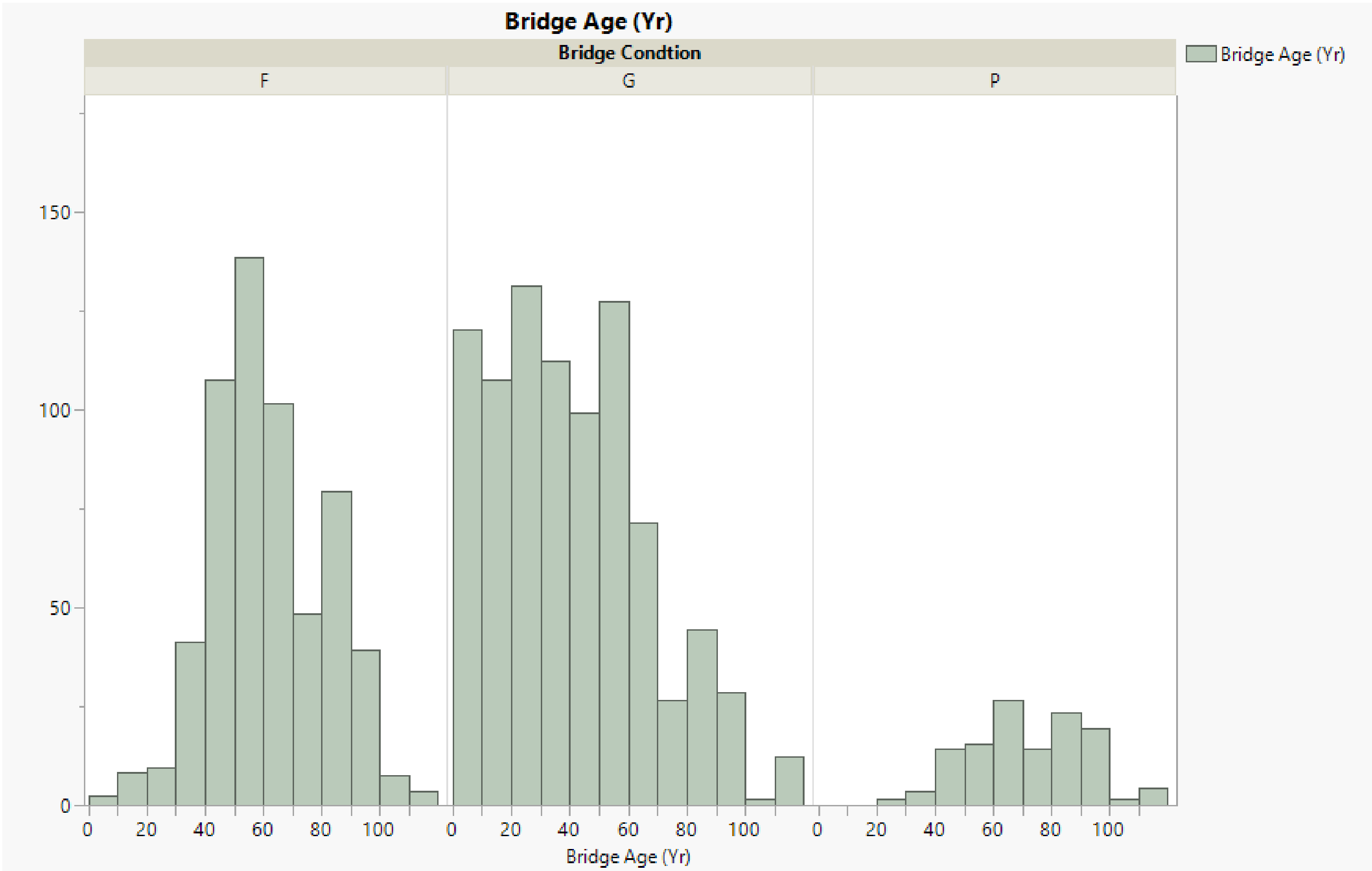

Figure 6: Bridge Count per Condition Rating by Age Group

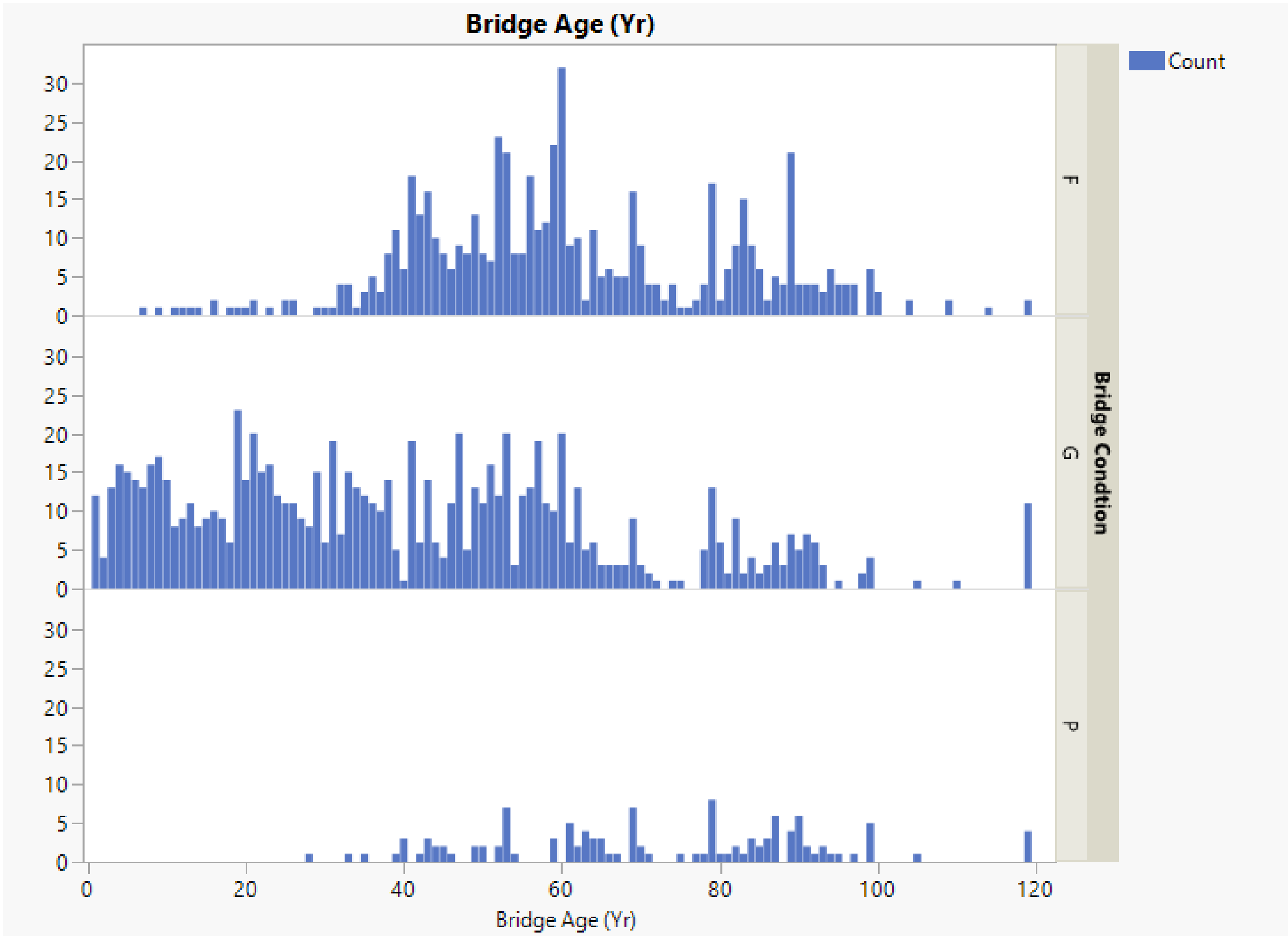

Figure 7: Bridge Age Distribution by Condition Rating

These graphs show that “Good” bridges skew younger, “Poor” bridges skew older, and “Fair” bridges somewhat normally distributed. For “Fair” bridges the maximum number of bridges are in the 40-60 years age range. For “Good” bridges the maximum number of bridges are in the 20-40 range and for “Poor” the maximum number of bridges are in the 80-100 range.

We also investigated other factors beyond age, location, and classification. For example, Figure 8 shows the average span length of bridges in each condition rating and Figure 9 shows the full distribution, both which show that there is not a substantial variation.

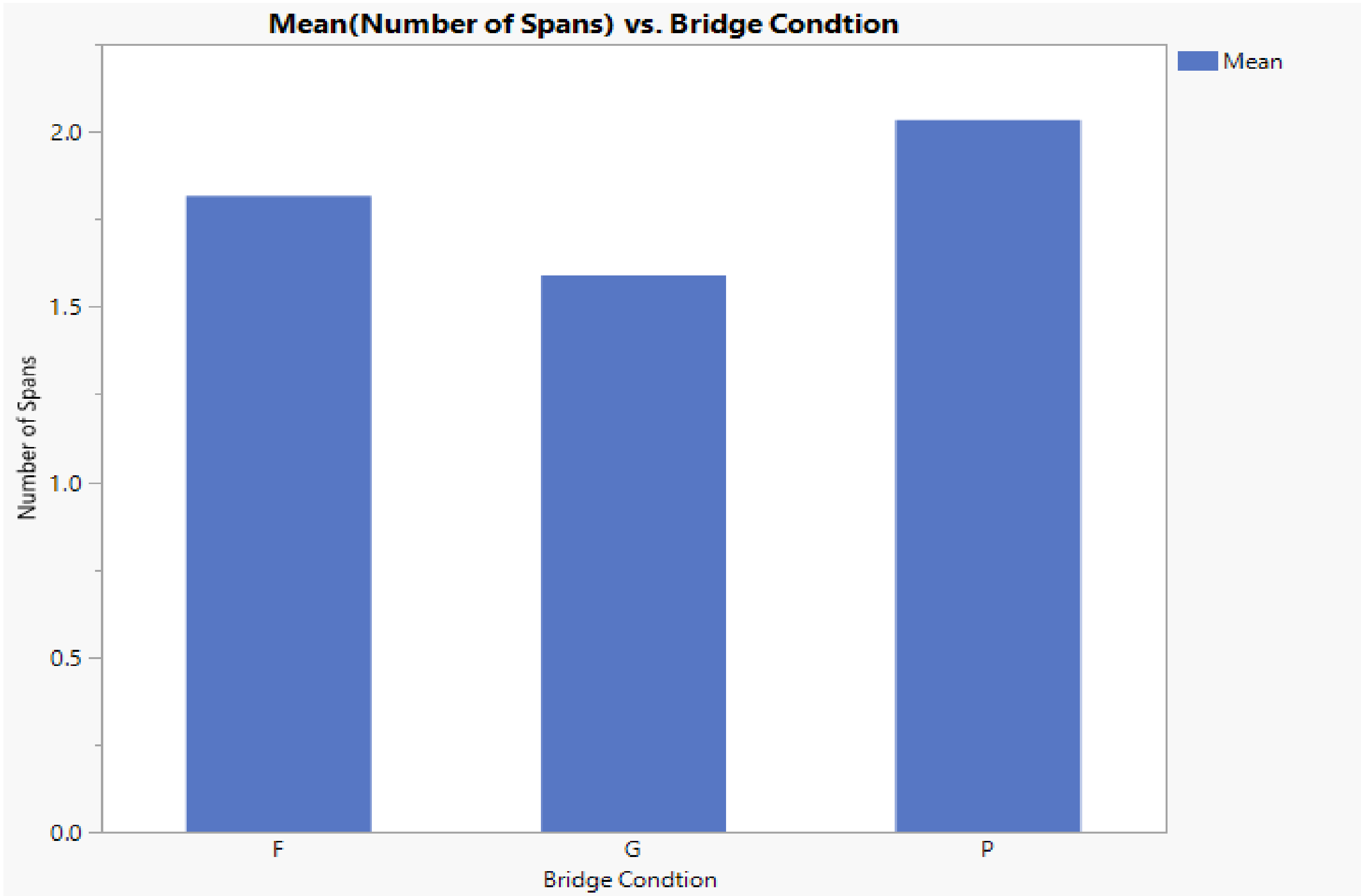

Figure 8: Bridge Condition by Average Number of Spans

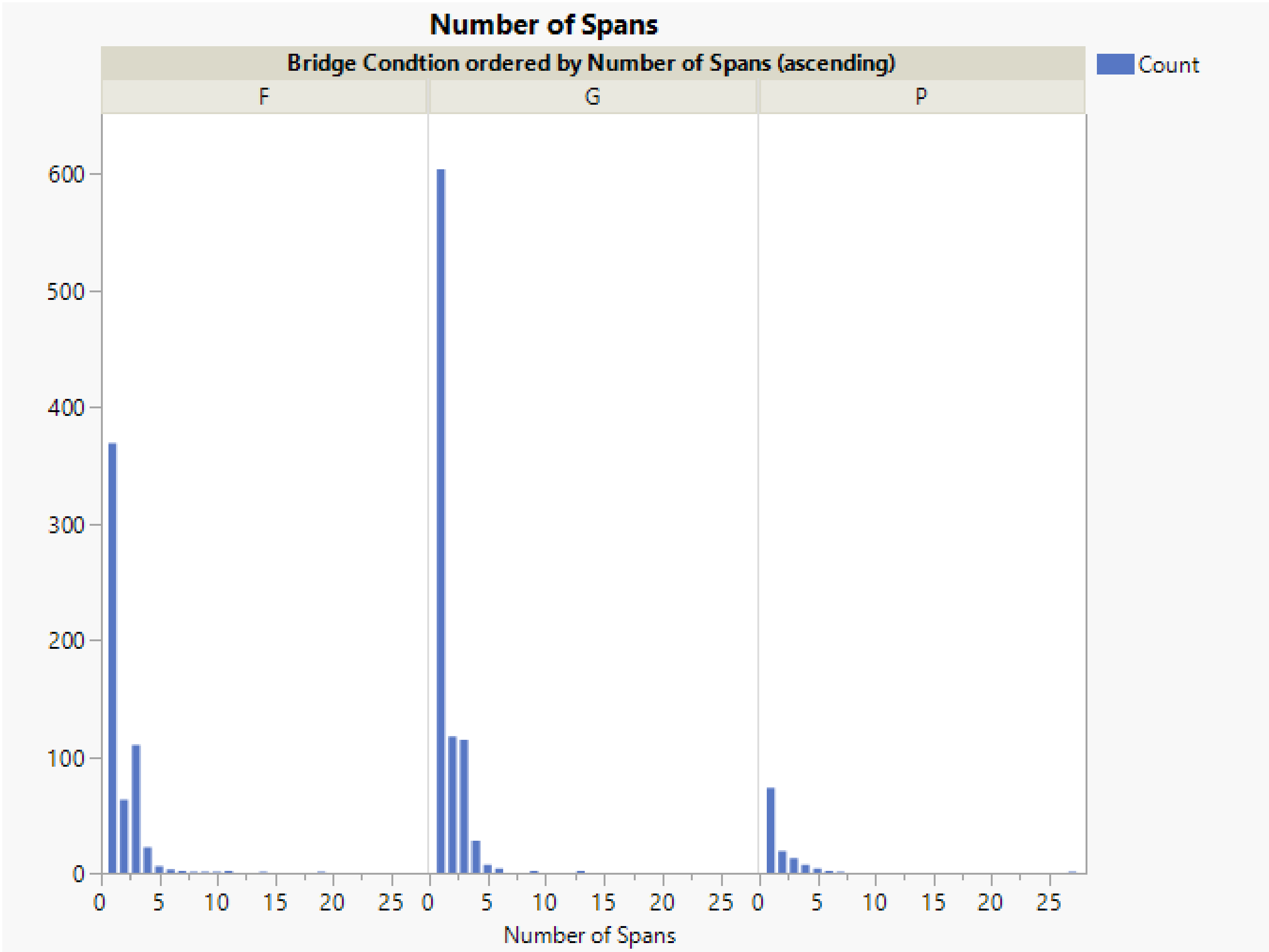

Figure 9: Bridge Distribution by Span per Condition Rating

For a complete analysis of bridge deterioration and RIS adherence, we would recommend selecting a representative sample of bridges from each Tier, each Location (County), and each Age group. The number of bridges from each sub-category would be the same percentage of the total sample set as the total bridge count of that sub-category within the entire bridge inventory. We would also recommend selecting specific bridges of interest in addition to the representative sample, for example bridges that cross-state borders, interstates, and historic bridges. This would help ensure that future deterioration curves are not only representative of the average bridge with each set of shared characteristics but would also capture and track outliers to see if those bridges have atypical interventions and how that may impact bridge condition, deterioration, and RIS adherence. As seen in the data summarized above, it would be beneficial to use Bridge Age, Tier and Location as categories when selecting the sample data set for analyzing condition deterioration of the bridges and testing an RIS adherence measure.

Beyond the summary analysis, we also combined bridge inventory data with intervention data (maintenance, repair, and rehabilitation) that was available despite the COVID-19 impacts. This intervention data was provided by NHDOT through exports from the “Activity Log” database.

This combined data is available in the excel file named “CobminedDataset_2021-06-29.xlsx” provided with this final report. This is the first step developing an RIS adherence tool and in being able to correlate deterioration (i.e., condition rating over time) with variations in intervention strategies (i.e., RIS adherence).

The datasets are combined by matching the structure numbers of the bridges. All structures have bridge detailed characteristic data (e.g., age, location, tier, span length). The structure numbers are also associated with Log IDs from the “Log” datasheet and subsequently associated with Activity IDs and descriptions. If there are multiple Log IDs for a bridge, the Log IDs are put in different lines in the same cell in the row for the bridge. The respective Activity Date, Construction By, CostPE, Construction Cost, Project No and Input By for the Log ID are placed in the same row. Future research can use updated Activity Log data and any other intervention data that was not collected during this project timeframe due to COVID-19 restrictions. The collection and organization of the intervention data should be coordinated with any ongoing changes to asset management plans and programs.

RIS Adherence Factor Survey

Survey Overview

A general overview and detailed deployment plan for a potential research survey is included here and available to the NHDOT for future projects. The information and actions are recommendations based on the work completed in this project and should be revisited and edited for any future research context.

The Recommended Investment Strategies (RIS) for girder bridges include a variety of activities grouped into three categories: Maintenance, Preservation, and Rehabilitation. To develop any RIS adherence measurement tool, a numerical weight is needed for each RIS activity to represent its relative importance to final bridge performance outcome. The goal of this survey is to create the weighting scheme that reflects the relative effect of each activity and activity grouping on the bridge's performance, which in this case is the total expected lifespan. The survey attempts to reach a consensus using experts at NHDOT, relevant municipalities, and qualified academics/researchers to rank each activity, and the rankings will be used to calculate the weighting factors.

The recommended approach for this is to use a multi-round survey, most likely a Delphi study. Round one would include broader questions that ask about the relative influence of activity groups on bridge lifespan and the relative influence of the overall timing of each type of activity. Round two would ask more detailed questions, specifically asking participants to complete pairwise comparisons for each RIS activity. Any additional rounds will re-ask the same questions from Round two. The quantitative pairwise data will be used to calculate RIS activity weights. More information about Delphi studies is included below.

Survey Protocol and Sample Text

The following text describes the survey, including the general protocol, sample informed consent data, and sample survey text. This text is similar to what would be used in a university Institutional Review Board (IRB) application, should this research be pursued in any future project(s).

The survey will be administered entirely online. It will be distributed via email and administered through Qualtrics (or similar) online software. The project team will work with NHDOT to create a list of suggested participants ranging from 5-25 total. The NHDOT will review and suggest any inclusion/exclusion criteria for these selected participants, prior to distributing the survey. For example, do all participants need to be NHDOT employees? If not, we recommend including key personnel from larger municipalities, cities, and neighboring states. As another example, do all participants need to have a minimum amount of experience?

The human subjects considered for this study will be qualified experts that have a significant amount of knowledge on the topic. Solicitation for participation will be done primarily through email. This will provide project participants with a brief description of the study, the contact information of the primary investigator, and the voluntary nature of the respondent's participation. The length of the survey and the participant's confidentiality will also be discussed.

No compensation or incentives will be provided to the participants in this research study.

A script like the following will be used via email to request the participation of interviewees:

"Dear <subject name>,

The University/Company is conducting a research project in collaboration with the New Hampshire Department of Transportation. The Recommended Investment Strategies (RIS) for girder bridges include a variety of activities grouped into three categories Maintenance, Preservation, and Rehabilitation. The goal of this survey is to create a weighting scheme that reflects the relative effect of each RIS activity on a bridge's total lifespan. The survey will use experts to rank each activity using pairwise comparison, and the rankings will be used to calculate the weighting factors.

You are included in this survey because of your relevant experience. Your participation is voluntary and confidential, all data will be anonymous, and you may withdraw yourself or your responses from the study at any time.

We anticipate that it will take approximately 5-10 minutes to complete the survey.

We appreciate your participation and look forward to hearing from you.

If you have any questions about this study either now or in the future, you may contact x by email at x@x.com and by phone at x."

The survey will take approximately 5-10 minutes to complete. We recommend giving the participants approximately two weeks to complete the survey and return it to our team via Qualtrics. One week after sending the survey to the participants, we recommend sending a reminder email and participants can reply with any questions or concerns before the deadline.

None of this data will be individually identifiable. The data will be collected by combining all responses within a developed spreadsheet. The experts will not interact with each other during the individual survey. Each participant will only communicate with the research team via email or phone. There will also be a post-survey group discussion via Zoom. Each participant will have the opportunity to interact with one another. This discussion provides an opportunity to share results with the respondents and collect additional feedback about the results and the research design.

All of the data will be anonymized through Qualtrics. Participant's names will not be connected to their responses or opinions. Participant names will not be published or recorded in the final report. The recorded data will be stored in a password protected web-based storage system. All information will be stored electronically and will not be shared with others outside of the research group. The data will be used in the progress meetings, progress reports, the final project report, and possibly within a publication. There may be a final presentation that will involve utilizing the stored data. The results of the entire study will be distributed to the NHDOT including any peer-reviewed publications and conference presentations. All participant names will not be listed in these publications.

There will be little to no risk of being involved in this research for participants. There will not be any risk including physical, psychological, legal, social, and economic risks. All participants will be anonymized after recording responses from the survey. The information being recorded and discussed is about their job tasks and their professional environment, including standard organization protocols and everyday tasks. There will not be any sensitive information being shared and will involve little to no risk.

There will not be any direct participant benefits from participation in this study. The results of the study could be used in ongoing research to develop recommendations related to NHDOT practices and for any use the NHDOT deems appropriate.

Sample Survey Text

Prior to the survey, the NHDOT Technical Advisory Group (TAG) will review and make clear suggestions regarding the list of chosen bridge activities. The current Recommend Investment Strategy includes the following activities and frequencies:

Table 1: RIS Activities and Frequencies

RIS Activity	Category of Work	Year (Frequency)
Clean and Seal; Clear Debris	Maintenance	Annually
Crack Seal Pavement	Preservation	5, 15, 25, 35, 45, 55, 65, 75, 85, 95, 105, 115
Pavement Inlay	Preservation	10, 30, 50, 70, 90, 110
Patch Deck and Substructure; Replace Membrane, Pavement, & Expansion Joints; Rehab Bearings; Touch Up Paint (if applicable)	Preservation	20, 40, 80, 100
Replace Deck, Membrane, Pavement, & Joints; Replace Bearings; Patch Substructure, New Paint (if applicable)	Rehabilitation	60
Replace Bridge (or superstructure)	Replacement	120

The first round of the survey will ask more general questions, including asking the participants to confirm the selection of these RIS activities, the importance of each type/category of work, and the need for specific activity intervals.

For timing/frequency, there are 5 options including 6 months, 1 year, 2 years. 5 years, and 10 years. Five options will give enough variation between the answers but will keep the options list small enough for the survey-taker to decide on an appropriate option. An example of the activity timing question for the first round is shown in *Figure 10*.

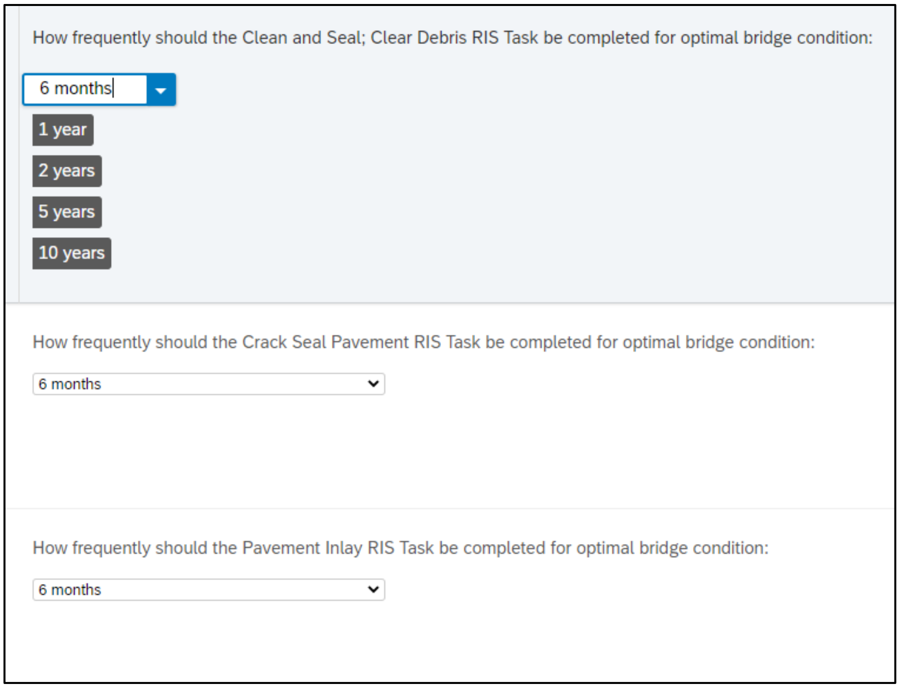

Figure 10: Frequency Questions and Options

The first round will also ask about sub-activities within the broader RIS activity. For example, there is an RIS activity that groups several tasks together, "Patch Deck and Substructure; Replace Membrane, Pavement, & Expansion Joints; Rehab Bearings; Touch up Paint." This grouping can be separated to better determine any differences in the influence of timing of these tasks. This separation of tasks is shown in the questions below. This will confirm the groupings the NHDOT put together and can validate or modify the of grouping several tasks together.

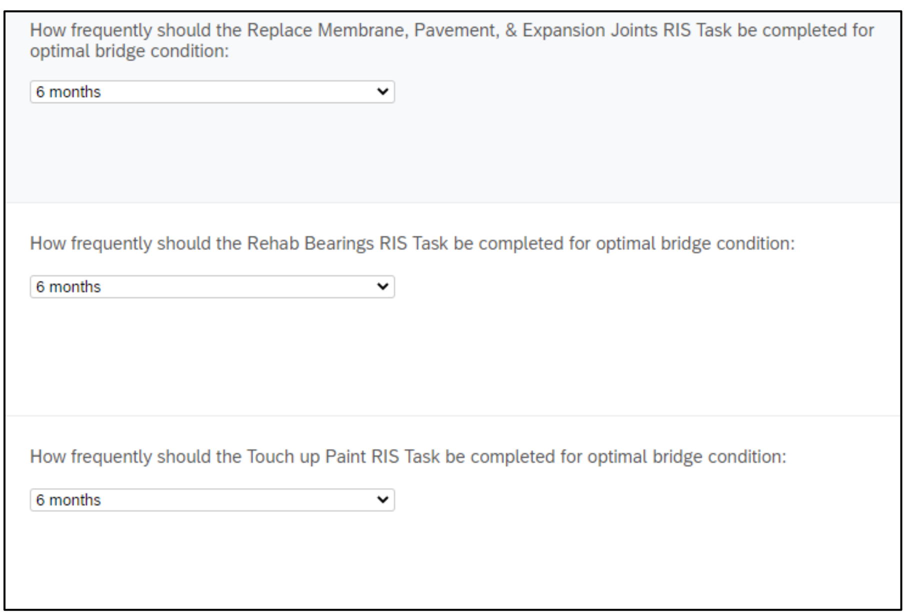

Figure 11: Separate Frequency Questions for Each Item in a RIS Task

For the importance of each activity, there are two types of ranking questions shown below. The first option is a “Selection Box” method. The user can click on a task and then move this task up or down with the side arrows to better place the task according to importance.

Figure 12: Selection Box Ranking Question

The second option is a “Drag and Drop” ranking question. The user can click and hold down on a task to then move up or down in the ranking list for importance. This is likely the easiest question format to use for ranking criteria.

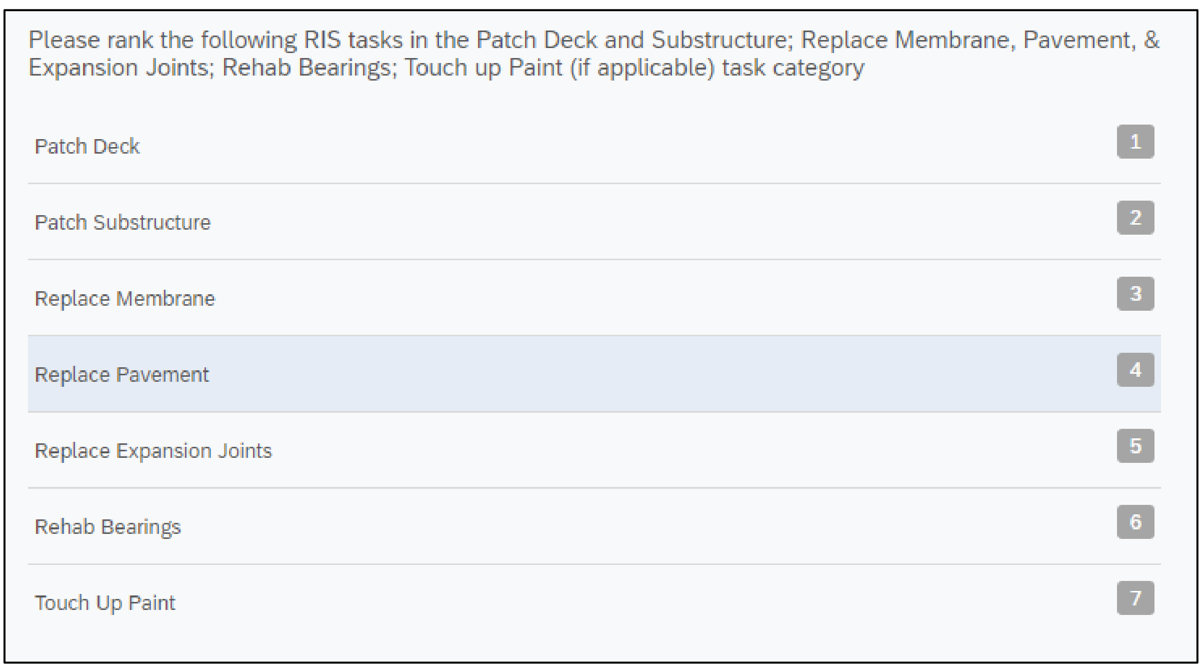

Figure 13: Drag and Drop Ranking Question

By separating each sub-task within the RIS activity, the survey can confirm or modify the organization of RIS activities and provide more detailed ranking in subsequent survey rounds. *Figure 14* shows a sample question like this.

Please rank the following RIS tasks in the Replace Deck, Membrane, Pavement, & Joints; Replace Bearings; Patch Substructure, New Paint (if applicable) task category

Replace Deck	1
Replace Membrane	2
Replace Bearings	3
Replace Pavement	4
Replace Expansion Joints	5
Patch Substructure	6
New Paint	7

Figure 14: Separation of Each Item in RIS Task for Ranking Question

Influence on bridge lifespan can vary for each activity based on planned frequency, completion on schedule, overall completion, and current bridge health and performance. *Figure 14* and *Figure 15* provide two approaches for asking participants to account for these variations. As previously described, if the participants indicate a preference to separate sub-tasks within broader RIS activities, they would be separated in these questions as well.

In between bridge replacements, which task is most important to complete and be completed on time:

Clean and Seal; Clear Debris	1
Crack Seal Pavement	2
Pavement Inlay	3
Patch Deck and Substructure; Replace Membrane, Pavement, & Expansion Joints; Rehab Bearings; Touch up Paint (if applicable)	4
Replace Deck, Membrane, Pavement, & Joints; Replace Bearings; Patch Substructure, New Paint (if applicable)	5

Figure 15: Importance According to Completion on Schedule

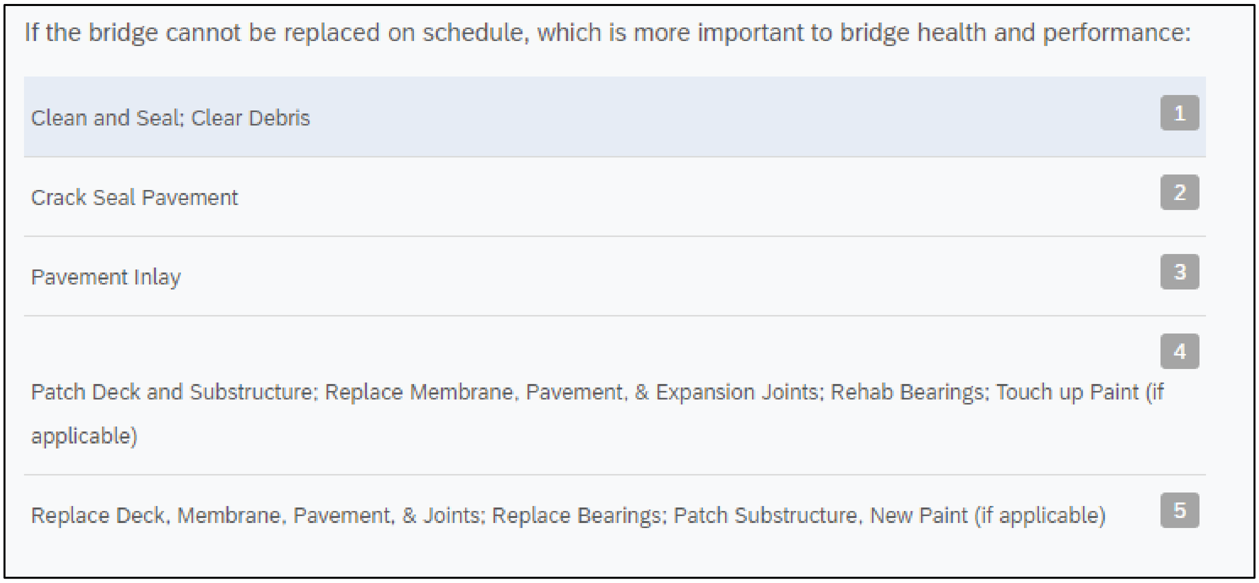

Figure 16: Importance to Bridge Health and Performance

The results of the first survey will be used to develop the questions for round two and any subsequent rounds. he RIS tasks will be broken down in more detail in order to complete pairwise comparison.

Pairwise Comparison

There will be a paired comparison for each activity to accurately receive a group ranking of importance. The table below displays the possible intensities of importance the participant can select ranging from 1 to 9; 1 being of equal importance and 9 being of extreme/absolute importance.

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two criteria contribute equally to the objective
2	Slightly More Important	
3	Moderate Importance	Experience and judgment slightly favor one criterion over another
4	Moderate to Strong Importance	
5	Strong Importance	Experience and judgment strongly favor one criterion over another
6	Strong to Very Strong Importance	
7	Very Strong Importance	A criterion is strongly favored and its dominance is demonstrated in practice
8	Very, Very Strong Importance	
9	Extreme/Absolute Importance	The evidence favoring one criterion over another is the highest possible order

Participants will select a ranking from 1 to 9 of importance for the most important activity. Shown below is a sample question within the Qualtrics survey. It displays two RIS bridge activity options and an area to rank the most important of the two items on a defined scale. For example, in the image below, the participant chose the "Crack Seal Pavement" as the more important activity and determined the intensity of importance as 6 (Strong to Very Strong Importance) over the "Clean and Seal; Clean Debris." This process will be repeated for all of the activities included in the list.

All of the RIS activities, including if modified by Round one, will be compared using pairwise comparison. Each option is displayed in a row and the corresponding column using the given importance scales. The sum of each row is normalized and then placed into the last column as a local weight. This local weight column is then used for the final table when each activity is placed in the left-hand column and is compared to each of the alternative activities in the top row. Each cell will be calculated by multiplying the local weight of the activity in the columns by their respective comparison values and summed up. The final column is computed numbers which will represent the amount of attention the RIS bridge activity should receive.

As an example, a pairwise comparison table is shown below. Each of the alternatives, one through three, are listed in the top row and the far-left column. These are alternatives for a technological advance for the issue and topic that was being discussed. Each of the alternatives in the far-left column were compared to the alternatives in the top row, then reciprocated where appropriate. A final weight was calculated for each row and ultimately each alternative. This weight could help determine future evaluations which could involve cost, time, and difficulty. After the weights were calculated, the maximum eigenvalue and the consistency ratio can be determined.

Table 2: Pairwise Comparison Example

Technological advance	Alternative 1	Alternative 2	Alternative 3	Weight
Alternative 1	1	3	7	0.643
Alternative 2	1/3	1	5	0.283
Alternative 3	1/7	1/5	1	0.074

λmax = 3.066.
Consistency ratio (CR) = 0.056.

Delphi Studies

The Delphi method is considered one of the three best known techniques when attempting to create a consensus (Blackwood and Currie, 2016). This method can include elements of both qualitative and quantitative (Fink-Hafner et al., 2019) and can be used with a mixed methods design, more frequently utilizing quantitative data. There are several different types of the Delphi method and the method can easily be combined with another method. Each method and use of the Delphi are unique due to the number of rounds, experts used, and type of consensus being reached varies with each conducted survey.

The Delphi method was originally used as a forecasting method, can be used for a range of needs including identification of a research topic, specification of possible research questions, preliminary investigation of causal relationships, and definition of any theories (Fink-Hafner et al., 2019).

The Delphi method is a process that involves both the researcher and the selected group of experts to complete a series of detailed questionnaires. This survey method relies heavily on the experts' feedback in order to moderate the continuing process (Devault, 2018). There are many opinions on whether the experts should be interacting or kept separate from one another. Some believe there should be consistent interaction between the entire group of chosen experts in order to achieve this goal (Fink-Hafner et al., 2019). Others believe the individuals should remain anonymous from each other in order to receive honest answers (Devault, 2018). The overall goal is to reach a reliable consensus regarding the specified topic being analyzed (Hesse et al., 2017).

The opinions of experts are recorded several times throughout this process by completing several repetitions of the same survey, each one having a different goal. The data from each survey will be analyzed and incorporated into the subsequent round of the survey. This means that each participant will see their response and the response of the entire group from the previous survey while completing the subsequent survey.

When the feedback is given back to the participants, it will allow for reconsideration and reevaluation of the survey questions (Hesse et al., 2017). Participants also have the opportunity to provide anonymous feedback in order to avoid bias and direct confrontation (Fink-Hafner et al., 2019), including additional comments to clarify their choices and opinions. Results for each question or the entire survey will change from round-to-round and ideally lead the group to a final consensus (Hesse et al., 2017).

A recommended survey size according to "Delphi Method: Strengths and Weaknesses" are panels no fewer than 10 participants and no greater than 1000 participants. A selected participant group typically ranges from 10 to 100 experts. A committee is also recommended to create the schedule and run the in-person discussions if that is the chosen method. There should be some sort of criteria to qualify the participants as experts with minimum qualifications, while still having a broad range of individual viewpoints in regard to the criteria being analyzed (Fink-Hafner et al., 2019). The expert's opinions could also be weighted depending on their experience level based on a created ranking.

Prior to the survey being distributed and interviews being coordinated, good knowledge of the subject will be gained from the prior literature review. There are several ways to begin the first round of interviews and surveys. One specific way to conduct the interview is to leave it very open-ended for the expert to respond honestly and identify specific elements, indicators and issues and prepare a questionnaire (Fink-Hafner et al., 2019). This can allow decision makers to develop the future questionnaire and survey based upon what is missing from within the literature review task. However, some researchers feel the decision makers should develop the entire first round survey and begin the interviewing process as this will ultimately save time and money. In (Fink-Hafner et al., 2019), researchers starting with quantitative surveys will typically identify elements as the first step. They will then look for validation as a second step and a consensus as the third step within the first round. This is the process recommended for the RIS adherence factor weighting.

It is ideal to have indirect interaction between the chosen experts and participants (Fink-Hafner et al., 2019). It is likely the opinions and answers given by these experts will converge as the rounds increase.

The interaction can either be face-to-face with the interviewer or through an online link to a survey. The RIS data can be obtained more quickly and easily online. The experts do not have to be grouped together when conducting interviews, they can be separate and have the results be individualized. If the Delphi method is being utilized via online methods, the experts could easily remain anonymous to one another while recording their opinions and answers.

There is a tendency for the judgements of the experts to converge (Fink-Hafner et al., 2019). The researchers designing the survey have the most control over the responses desired and types of questions being asked. These decision makers should be prepared to give structural feedback to the participants and analyze the results statistically for estimation of the next round of questions (Fink-Hafner et al., 2019). From "Delphi Method: Strengths and Weaknesses," the article states "The survey will be what the decision makers morph it into, and what results they would like to obtain."

The Delphi research design can be completed with two main phases. The first phase will include the literature analysis, initial interviews with experts, final list of experts, gathering research material, analysis to evaluate and select elements for review, and create the preliminary questionnaire for the first round of interviews. The second phase will likely include the conduction of the first-round interviews, analysis of the first-round results, preparation of the second-round questionnaire and then completing the second round. The final step in the second phase is to analyze the results recorded from the second-round interviews.

The Delphi method is conducted over several rounds of interviews and surveys with each one having a different goal. A Delphi questionnaire changes from each iteration, as within the first round, the survey can be more qualitative in order to identify various possible elements relevant to the research problem. Within the second round, the questionnaire is able to be more quantitative and standardized and a ranking will be used for the results (Fink-Hafner et al., 2019). The third round will be based on the second-round results while continuing to rank elements and validating if they are relevant. The decision makers can make further changes to the survey. The number of rounds to be completed will be dependent on the stability and consensus being developed from each round.

The first round would be completed using literature review or any previously completed surveys about the desired topic. Within the first round, a selection of experts can be contacted regarding the reviewed literature. They can be consulted regarding the direction of the first survey for the type of focus and desired results. The first round is likely to include qualitative information to identify the main elements of the survey.

The first round will typically involve an open-ended questionnaire and have very broad questions in order to encourage brainstorming (Devault, 2018). This questionnaire is developed to gain a sense of knowledge about the type and level of expertise of the respondents. The questionnaire will ask for specific information about the topic of focus in order to rank the experts and will hopefully generate clear responses. Once the answers are received, another survey is generated and distributed using the knowledge previously gained. Adjustments can be made to either focus the questions more or improve the time limit of the survey (Devault, 2018).

The second-round information is gathered using the first round's compiled results which will be more quantitative as the ranking scales are now being used. The second round is typically close-ended questions which are aimed to be more direct based off of the first-round questionnaire (Hesse et al., 2017). The experts are ranking the first-round results, which are the original opinions given by the other experts. It is very important the selected experts are of a certain experience level as to not give insufficient or misleading answers regarding the area of focus (Devault, 2018). The goal is to reduce the range and amount of given answers following the second round.

The second-round results will then be compiled with the results from the previous round. The third round allows the committee to modify the survey and make any changes based on the second-round results. The experts participating in the review will then be asked to review the full spreadsheet including the second-round results and answer based on all the prior opinions (Hesse et al., 2017). The experts are given the opportunity to review their answers compared to the entire group and either keep their original answer or modify it based on the group's consensus (Hesse et al., 2017). If an opinion were given different from the consensus, a reason could be written down to defend an opinion. These rounds are repeated until stability, and ideally consensus, is reached.

Following each round, data analysis can be completed to determine the stability of the questions and the level of agreement between the experts. It is anticipated the answers will improve and eventually converge (Hesse et al., 2017). It is hoped there will be more substance to each opinion as each round influences the following round. These distributed surveys can certainly be completed through email but can also be completed and recorded through a research application. This survey research application will integrate the recorded data, summarize and display the results, and then analyze the results for each stage of the survey (Devault, 2018).

A coefficient of variation (COV) can be utilized for each question and compared to a decided range of values (Hesse et al., 2017). The range can show a level of convergence for each round's results. A convergence value lower than 0.5 is considered to be converging towards the mean value (Hesse et al., 2017). If a value is within the range of 0.5 to 0.8, the response was nearing convergence and should likely be analyzed further to understand the trend. If the value is over 0.8, the value is not nearing to convergence.

Within "Using Expert Opinion to Quantify Uncertainty in and Cost of Using Nondestructive Evaluation on Bridges," a nonparametric method was chosen to analyze stability. The Spearman's Rank Correlation Coefficient method was selected to further process the data being collected after each round. As seen in *Figure 17*, the rank correlation can be calculated. The "d_i" variable is the difference between ranks of the respondents for the "i-th" question. The variable "n" is the number of respondents. If participants dropped from each round, the participant count from the final survey was used. The calculated value is then compared to a critical value from Spearman's tables. If the calculated value is greater than the critical value, then the responses received are stable. The closer the value is to "1", the results are considered stable and if the results are closer to "0", the results are believed to be unstable.

$$r_S = 1 - \frac{6 \sum {d_i}^2}{n\left(n^2 - 1\right)}$$

Figure 17: Spearman's Rank Correlation Coefficient Equation

An advantage with the Delphi method is that it includes qualitative and quantitative approaches with the use of constructive criticism. It is written in a journal article, "Delphi Method: Strengths and

Weaknesses," that the data analysis methods for quantitative Delphi studies have seen greater development than for qualitative ones. The Delphi method allows for indirect confrontation of experts as the experts can avoid meeting and discussing the topics with one another. This is also useful as the experts can be fully honest with the decision makers and facilitators when giving their opinions and responses. It is beneficial to see the areas of agreement or disagreement within a specific focus or area as there will be a wide range of expertise (Blackwood and Currie, 2016). When completed in a group setting, there can be loud discussions or even confusion regarding an individual's opinion. This method allows for deep thought and validity of their answers when completing each of the rounds.

Another benefit with the Delphi method is that each expert is one-on-one with the facilitator and information can be easily recorded without distraction or influences which can lead to a very rapid consensus (Blackwood and Currie, 2016). If the experts' locations are spread out, an online process may be easier rather than an in-person meeting. With the method of interviewing and recording answers directly, it is feasible to input into a spreadsheet. In "Delphi Method: Strengths and Weaknesses," it is stated that the Delphi method goes beyond simple expert estimations due to the control over the selected questions, the process of interviewing and re-interviewing, and the analysis of the recorded results.

There can be a lack of agreement within the decision committee as to how to analyze the recorded results and conduct the interviews which can be a disadvantage with the Delphi method. This method could also be very time consuming and involve a large workload for both the interviewers and experts. Some participants may not be in favor of handwriting their ideas down and may prefer an interview format. The participants may even back out if the process is taking too long or if the time commitment is too large as they can become distracted in between rounds and disagree with the process. It is important the participants have enough time to complete each iteration of the survey (Devault, 2018).The experts may also believe there is "less ownership of ideas" with the anonymity of the surveys (Fink-Hafner et al., 2019). If the experts are in contact with each other, "these ideas and opinions that they are giving may not be truly independent or honest." Technical issues may also arise when completing the method using an online survey. A weakness of using the Delphi method is that when an opinion differs from the group consensus, it may not be properly investigated (Blackwood and Currie, 2016). The overall success of the study is dependent on the quality of the chosen participants, and this can also be considered a weakness of this method.

Within "Delphi Method: Strengths and Weaknesses," there are two main suggestions to help the weaknesses within the Delphi method. One of these improvements could be using the Delphi method along with another method to compliment the process. The next suggestion is to apply an online technique in order to help the strengths and lessen the weaknesses of the method.

This method may not be useful when utilized in a single in-person meeting. The NHDOT was interested in gathering a list of experts and having a group meeting for a few hours to discuss specific questions and rankings. After each round, the results will need to be compiled and recorded. It may take additional time if the questions will need to be restructured and reformatted. There may need to be several in-person meetings in order to efficiently organize and distribute the newly formatted surveys. If this method is utilized in a one-time meeting, it can possibly take hours to complete at least three rounds and conduct interviews and analyze the information. While an in-person focus group or other workshop exercise could be beneficial, a Delphi study is only recommended for an online survey.

Weighting Methods

There are more options beyond pairwise comparison that could be used to collect expert input and calculate weights. These options are discussed below with pros, cons, and each method's applicability to this work.

Rank Order Centroid Method

The rank order centroid method models relative ranking between a set of criteria according to importance. This method will generate a distribution of criteria weightings that is statistically comparable to that by a panel of subject matter experts performing various algorithmic approaches to defining relative weights. The experts can easily rank several items rather than assign their weights. The criteria will be placed in order with no regard to weights. This method will compute a number which is a value estimating the distance between adjacent ranks on a normalized scale. The centroid of all possible weights will be identified while maintaining the rank order of objective importance.

$$w_{(i)} = \frac{1}{m}\sum_{k=i}^{m}\frac{1}{k}, \quad i = 1, 2, \ldots, m$$

The weights being produced will reflect the centroid (center of gravity) of the simplex defined by the ranking of the attributes. Stable weights will be produced, and these weights reflect the centroid of the simplex defined by the ranking of the criteria. The more criteria will mean there is less error for the ranking criteria.

<u>Pros:</u> Rank order centroid is a reasonable method for an expert-driven survey. It's a very simple approach and can be replicated and revised according to the need for weights or rankings. This method is quick to learn and is not very complicated to understand.

<u>Cons:</u> The generated weights can be considered too "steep" and will assign relatively greater weights to the most important criterion. This will not generate the final weights as AHP will be used to compare the final item rankings.

<u>Applicability:</u> The recommended initial weighting method is the rank-order centroid method as it can be easily applied to the results of an expert survey and easily adapted and replicated for future needs. Once the RIS task weights are calculated from the rank-order centroid method, the AHP method is recommended to be utilized to create final weights for each RIS task from the expert survey.

Direct Entry

The direct entry method involves the direct assignment of value to various levels of a criterion. This method is mostly used for online preference elicitation. Each object that is being ranked will be separately assessed on a scale from 0 to 100. These weights will not add up to 100 and should be normalized at the end of the process. Direct rating is highly recommended when the performance evaluation will rely on using a larger number of criteria and when respondents do not want to use complex weighting methods.

The direct entry method can use a scale from 1-5 or 1-7 for importance ratings. Each criterion weighting can be altered without affecting the other criteria weighting. First, the decision-maker ranks all the criteria according to importance. Decision-makers can compare criteria by using a ratio scale. The criteria weights are calculated based on the weights suggested by the respondents. This method does not constrain the decision-maker's responses.

<u>Pros:</u> This method is quite easy since criteria weights are assessed by asking the respondents to assign values of the criteria. An advantage of this method is that it does not require any prior knowledge of the survey process and can be easily applied to survey-based criteria weighting. Another benefit of using this method is making it possible to alter the importance of one criterion without adjusting the weight of another. This is a very simple and easy way to assign weights and ranking to a list of criteria.

<u>Cons:</u> A disadvantage of direct entry is there is a little variation of the averaged weights. Another disadvantage of this method is the high potential for biased information and tendency towards the low variation of the criteria weights.

<u>Applicability:</u> This method applies to the ranking of RIS tasks. It will be a very quick and easy survey to format, complete, and record responses. However, there can be potential biases for the decision-makers and the recorded results can vary greatly. The decision-makers will view the list of RIS tasks and rank them according to importance or give them an importance rating from a given scale. The final ranking can be calculated and the weighting for each task will be calculated.

Ratio and Swing Weighting/Ranking

<u>Swing</u>

The swing weighting method is subjective. This method requires the development of an extreme scenario, where is hypothetical worst-case scenario is presented. The decision-maker selects an alternative with the worst outcome and then picks the criteria whose performance is likely to change or swing from its worst to its best. The criterion that might be enhanced to improve the overall situation the most is chosen as the most important criterion. The most important criterion and most preferred swing is given a higher weight and receives 100 points.

The criteria whose performance the decision-maker would like to change from worst to best level is selected again and will be given a value from 0 to 100. All the other criteria are weighted similarly and will receive point values between 0 and 100 points. This “0 to 100” value represents its relative importance to the most important criteria.

The next step is to obtain the average normalized weights and normalized weights interval. A matrix is first created where the top row defines the values in terms of relative importance while the left column represents the range of variation values. A value measure should be assigned that is most preferred to the decision and at the same time has a large variation to the upper left of the matrix, labeled “R” in the example. A value measure should be assigned that has the worst preferred importance and has the smallest variation in its scale is placed to the lower right of the matrix, labeled “Z” in the example.

Table 6: Swing weight matrix template

		Importance of the value measure to the decision makers		
		High	Medium	Low
Variation of Scale	High	R	S	T
	Medium	U	V	W
	Low	X	Y	Z

$$W_i = \frac{C_i}{\sum_{i-1}^{n} C_i} \qquad (9)$$

Where C_i is the unnormalized swing weight.

(a) $C_R > C_i$ for all value of i in all other cell

(b) $C_U > C_X, C_{V,} C_Y, C_W, C_Z$

(c) $C_S > C_{V,} C_T, C_Y, C_W, C_Z$

(d) $C_X > C_Y, C_Z$

(e) $C_V > C_Y, C_W, C_Z$

(f) $C_T > C_W, C_Z$

(g) $C_Y > C_Z$

(h) $C_W > C_Z$

Rules for consistency are necessary and the condition and relationships above for nonnormalized swing weights should be followed. Stakeholders typically need to make a compromise between the level of importance and level of variation in the measurement scale. This allows stakeholders to assign arbitrary large weight to the top left-hand side of the matrix (100 or 1000) and low weight in the bottom right corner (1).

Table 7: Element of the swing weight matrix

		Importance of the value measure to the decision makers		
		High	Medium	Low
Variation	High	100	85	35
of	Medium	80	40	20
Scale	Low	50	10	1

This method begins with assessing different alternatives to sway the importance of one criterion over another. The decision-maker can swing one criterion from least important to most important. The criterion with the most swing and movement to most important is given the highest rank and weight (ex, 100 or 1000). The other criteria are given percentages of the highest criterion weighting. The swing weight matrix is very detailed and is an effective way to describe and determine importance weights.

Pros: There is a check for consistency that will help validate the assigned rankings and weights. This method has a step-by-step approach and can be learned but it may need some practice and time.

Cons: It's a very detailed weighting method and it may be hard to replicate and revise according to different desired outcomes. There is also quite a small scale for importance and variation that the decision-makers may need to compromise on. If this survey is being analyzed by different people, it may be hard for multiple people to learn and master this method of analysis. This method is a very subjective approach.

Applicability: This method can be applied to the expert survey. However, I think this will be a difficult method to master in a short period and with little practice. I also think while it can be applied to the results from the expert survey, it may be too confusing of a method to follow as well as follow the consistency checks. This may be difficult to explain over a survey information block. This may be an appropriate method to utilize with in-person surveys though it will take a longer amount of time.

Ratio

The ratio method is a subjective weighting method. This method requires decision-makers to input and rank the relevant criteria according to their importance. Once the ranking is completed, the weights for each criterion will be assigned. The least important criterion is assigned the value of 10 and the other criteria are assigned multiples of ten. The resulting raw weights are then normalized to sum to one. Any increase in the assigned weights is subjective to the decision-makers. The difference in weights reflects the differences according to the importance of the criteria. The normalized weights will be calculated by dividing the raw weight of the criterion by the sum of all the assigned weights. The normalized weights will be equal to 100%.

Pros: The ratio method is a very simple and direct approach and can be applied to the expert survey. It's a very basic method to learn and apply. The weights assigned in this method are normalized at the end.

Cons: This may not be as accurate as of the rank-order centroid method. This is a very subjective ranking method. The spacing between rankings is subjective to the decision-maker. The ROC method is based on the overall ranking.

Applicability: Based on the expert survey, this method can be applied to the ranking and weighting of criteria. It will be an easy method to learn if being passed on to several different departments at the NHDOT.

Analytical Hierarchy Process (AHP)

Pairwise comparison, when utilized in the Analytic Hierarchy Process, requires participants to score/rank the importance of one factor relative to another factor, in this case, RIS activities. Pairwise comparison is a useful method to analyze the majority vote from participant responses and determine any differences and discrepancies from the recorded results. AHP achieves the goal of deriving weights for set criteria by having the decision-maker make qualitative paired comparisons according to their perceived importance. Quantitative values, representing weights for each criterion, can then be calculated using linear algebra, eigenvectors, and eigenvalues. Researchers using AHP will ideally place their main decision problems into a hierarchy of more easily understandable subproblems. These smaller problems can then be analyzed independently of one another. The AHP method may be the easiest in terms of compiling information once results are received and redistributing the recorded results.

The decision-maker will compare the items to the rest of the group and give preferential importance as each item is ranked. All of the items will be compared to one another, and the numbers will be added up and normalized. The results from normalization will be the weights for each criterion. The level of importance table ranking items 1-9 should be referenced when assigning appropriate importance levels for each item.

Pros: AHP is a very effective method as the detailed nature of the comparisons helps decision-makers give complete, well-thought-out answers. Each comparison is completed using pairs which can make it easier for the decision-maker to pick one over the other. A consistency ratio can be completed to determine any variation with the survey responses. This is a method that has been tested numerous times and shows great results.

Cons: The importance scale being used can be too many options for decision-makers. Many of the descriptions and definitions can be considered too related to pick one over the other. It may not give a true comparison if experts will not think deeply about the importance scale and give an accurate rating. Since the comparisons are made using paired items, it may be difficult for the decision-maker to make a true comparison or pick one as more important over the other if the items are close together. This method asks for relative importance without a clear definition and reference to the importance scale. This can create a fuzzy response as decision-makers can make different assumptions and skew the ranking and weighting method.

Applicability: This would be a difficult method, to begin with as the matrix to evaluate comparisons will likely confuse the decision-makers. However, it is a great method to utilize and appropriately rank a set of items. It’s a detailed method that can calculate a very accurate ranking due to the step-by-step process.

Weighting Recommendation:

The project team recommends using pairwise comparison and AHP, as shown in the sample survey text and for the reasons described above. If pairwise comparison is not selected, for example if it is too time-intensive, then the recommended weighting method will be rank-order centroid. Each RIS task will be ranked in the expert survey. These weightings will be averaged together to create a final ranking of the RIS tasks. Once the final weightings are completed, the rank-order centroid method will be used. The centroid of this ranking will be identified. Then each criterion is given a distance away from the centroid. The ROC method can be used to calculate the first set of weights for each criterion.

Relevant Deterioration Modeling Literature

A review of bridge deterioration modeling and potential application for RIS and future bridge performance management.

The task of building deterioration models and deterioration curves is a systematic process. Deterioration models and curves help understand how a structure behaved in the past to specific loading and weather conditions to predict how they will behave in the future. Many transportation departments have already taken measures to build deterioration models and curves for their roads and bridges. Deterioration model building involves building predictive statistical models based on machine learning or other methods. Building deterioration consists of collecting the historical conditional data about the structure and plotting element level or holistic performance based on the time.

Nebraska Bridge Deterioration Curve Development

Nebraska Department of Roads had adopted an approach to predict the deterioration of the bridge components, which is based on the national average deterioration rates. The deck condition deterioration is considered every eight years, and the super and substructure condition deterioration rating is considered every ten years. Here, traffic volume, weather condition, structure, and material type were not taken into consideration. The condition ratings of the bridge components (deck, superstructure, and substructure) are obtained from 1998 to 2010 bridge inspection data to develop deterioration models for the bridges. The impact factors considered here were wearing surface, ADT, ADTT, deck protection, structure type, and highway district.

Deterioration Model Development System

Recently, NDOR has adopted "Pontis" as a Bridge Management System to avoid the frequent updates of NBMS, and AASHTO supports Pontis. It is mainly used to update the deterioration models based on transition probability matrices. Pontis deterioration models will be developed by using the inventory and condition data available in the database.

The project mainly reflects the budget allocation for the maintenance, rehabilitation, and replacement needs of the bridges utilizing predicting deterioration to calculate life-cycle costs. The national average deterioration rates are adopted to predict the deterioration of the bridge components, which is mainly: one drop in the deck condition rating every eight years, one drop in the superstructure condition rating every ten years. *The approach they have taken does not consider the impact of traffic volume, structure, and material type; environmental impacts specific to Nebraska Bridges.*

Factors considered in developing the deterioration models

Structure type, deck type, wearing surface, deck protection, ADT, ADT, and highway district.

Life-Cycle Costs Determination:

One of the main objectives of their project was to determine the life-cycle costs. Deterioration models are crucial to assessing life-cycle costs because maintenance costs and user costs are highly dependent on bridge conditions. The quality of these LCC-based decisions depends on the deterioration models' efficiency to predict the bridges' time-dependent performance and remaining service life.

The MR&R (maintenance, rehabilitation, and replacement) decision-making is mainly based on engineering judgment. The LCC assessment of proposed actions is not followed in the decision-making. Additionally, the deterioration rates are based on the national average deterioration rates, which don't reflect the bridges' actual deterioration rates. LCC assessment enables determining the costs associated with maintenance, rehabilitation, and replacement of the bridges efficiently.

Condition Ratings:

The condition ratings used for rating the bridge elements are the following:

State	Description
N	NOT APPLICABLE
9	EXCELLENT CONDITION
8	VERY GOOD CONDITION - no problems noted.
7	GOOD CONDITION - some minor problems.
6	SATISFACTORY CONDITION
5	FAIR CONDITION
4	POOR CONDITION
3	SERIOUS CONDITION
2	CRITICAL CONDITION
1	"IMMINENT" FAILURE CONDITION
0	FAILED CONDITION

Deterioration Curves:

Several condition rating curves are constructed for the project. Such as Age vs. Condition Rating for the bridge deck, super, and substructure in the year 2010 shows the number of bridges in each condition rating of the bridge decks

There are various types of wearing surfaces of the bridges, such as concrete, silica fume, latex concrete, low slump concrete, epoxy overlay, bituminous, timber, gravel, and other types. The ratings of the wearing surface are also considered in developing different curves. Deterioration curves of different materials in bridges over the years are constructed based on their condition ratings. The deterioration curves of other parts of the bridges (deck, substructure, superstructure, wearing surface, etc.) are also constructed separately based on their condition ratings over the years. The deterioration curves respective deterioration formulas are produced with condition rating as the dependent variable and age as the independent variable.

Deterioration curves for the replacement deck or other replacement parts of the bridges are constructed separately, which indicates no overlays. For each 4-5 years, the deterioration of the condition ratings is considered to determine the transition period. Different duration intervals to re-deck the bridges are used to construct separate deterioration curves for different years. The same approach is applied for the overlay. Finally, the different deterioration curves are produced based on different ADT intervals of bridges over the years. The same approach is also applied for the ADTT of the bridges over the years. A sample deterioration curve of this sort is shown below:

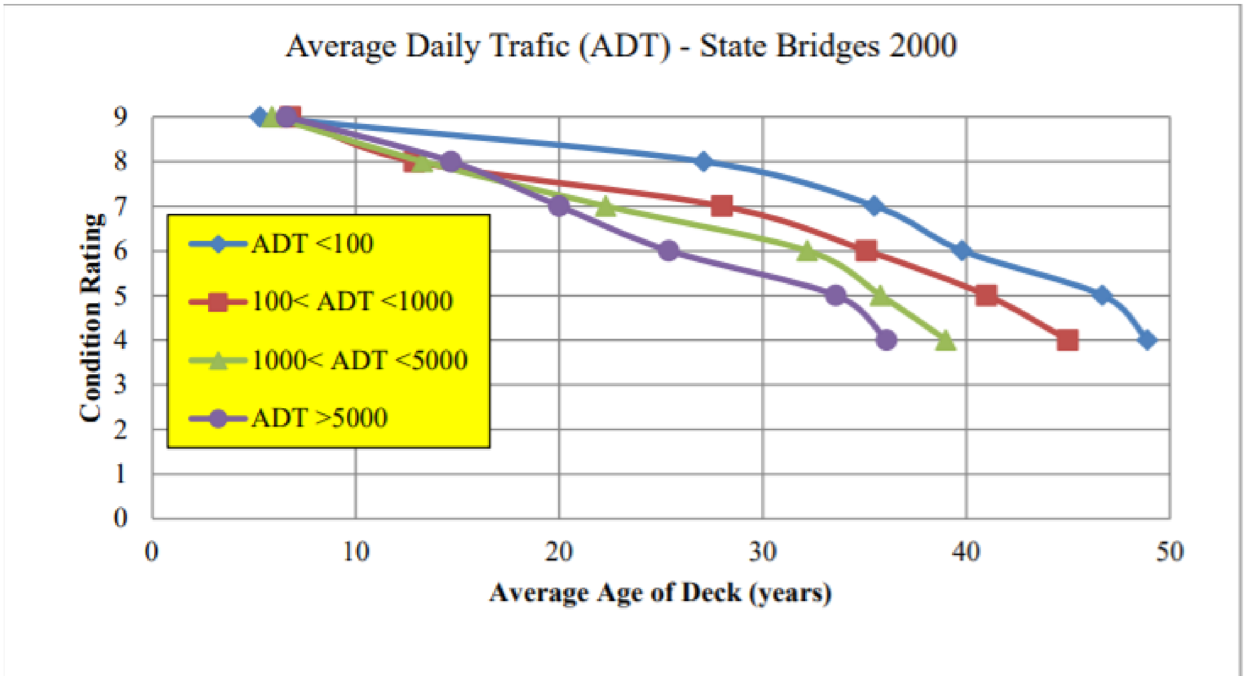

Figure 4.35 Deterioration curves of state bridge decks with different ADT- year 2000

Notable points of this project:

- ADT, county, Structure type, material type, component-based deterioration modeling, and deterioration curve development
- Ten levels of condition rating, so the bridges' condition can be categorized in a broad range.
- Deterioration curves are developed for different components of the bridges.
- Deterioration curves are also produced based on different maintenance types (e.g., re-decking, rehabilitation, etc.)
- A transition period of 4-5 years for each component of the bridges is considered and used for deterioration modeling.

Points that can be useful for other projects:

- To categorize the bridges by county, ADT for developing deterioration curves is helpful for other projects. Because after analyzing the condition ratings by considering these factors, we could see a particular variation of condition ratings
- Different deterioration curves can be developed for different bridges and varied by factors (County, Tiers, bridge age).
- Considering a transition period, which will be determined by analyzing the historical condition ratings, a probabilistic deterioration model can be developed to predict the condition ratings of different types of bridges in the future.
- The deterioration curve approach using maintenance types and wearing surfaces can be easily applied to the list of NHDOT RIS tasks.
- The LLC assessment can also be utilized when looking at the different RIS tasks and future costs. These developed deterioration models can then analyze life-cycle costs and RIS task costs for future maintenance, rehabilitation, and replacement projects.

Bridge Element Deterioration Rates (NYSDOT):

The project was to carry out extensive filtering, recondition the bridges' inspection data, calculate deterioration rates for the bridge elements, and develop a computer program to calculate the deterioration rates.

Several filters are developed and applied to remove the inspection data affected by rehabilitation, inspector subjectivity, vehicle/vessel collision effect on the ratings, and miscoding on the inspection ratings. Also, to investigate numerous factors that affect the deterioration ratings, e.g., AADTT, climate, DOT regions, ownership, design types, etc., a versatile cascading approach is developed to classify the bridge elements based on selected factors. A computer program is set to calculate deterioration rates based on Markov Chain and Weibull-based methods and compare them. Then using both the deterioration rating equations, deterioration curves are produced.

Based on discussions with NYSDOT, some bridge elements have been included in the computer program to calculate deterioration rates. "Superstructure Recommendation" and "Pier Recommendation" condition ratings are also included in the deterioration rate calculation. "Superstructure Recommendation" is a rating of the entire system comprising superstructure elements to describe best the inspector's opinion of the system's condition and ability to function) (a rating of the entire method comprising of "pier elements" to best describe the inspector's opinion of the system's condition and ability to function)

Notable points of this project:

- The bridges are broken into different components, and the rating for each element is considered.
- If a bridge, or one or more of its components, is reconstructed, then the bridge's rating or historical data before the reconstruction year is discarded.
- One of the most interesting aspects of this project is the condition rating of the bridges here are also categorized from 1 to 7. If two points improve a condition rating improvement of two consecutive inspections for a bridge to 7, then it is assumed that the bridge is probably replaced and reconstructed

Points that can be useful for other projects:

- The general approach can be applied to different variables of interest and for different components of the bridges, which means it can be tailored to RIS.
- It could also be helpful to develop different deterioration curves for bridges that never went through rehabilitation, reconstructed, or replaced bridges, and bridges that went through significant rehabilitation.

Determination of Bridge Deterioration Models and Bridge User Costs for the NCDOT Bridge Management System:

The North Carolina Department of Transportation has 17000 bridges under their supervision. They oversee the design, construction, maintenance, repair, rehabilitation, and replacement of the bridges.

Project overview:

BMS: The Bridge Management System of NCDOT works to store the inventory data, including bridge characteristics, inspection data, and rating information. The NCDOT also uses deterioration models and economic models to predict outcomes and provide network-level and project-level decisions.

Objective: This project's goals were to provide NCDOT with updated deterioration models and user cost tables for use in the BMS software.

Deterioration Model: The method of developing deterioration models was a deterministic approach with data of the bridge components grouped into families by a priori classifications. Additionally, a statistical regression method was developed using the survival analysis technique to address better the historical condition rating data characteristics, which produced probabilistic deterioration models for bridge components. This approach helped them with improved predictive accuracy over the previous method.

The Markov Chain Model:

The NCDOT uses a deterministic deterioration model, which is based on simple statistical properties. However, some of the problems they have are:

- They neglect the stochastic or time-dependent nature of the condition rating data.
- They neglect the non-normal statistical properties and the effect of censoring on the condition rating durations, limiting the models' prediction accuracy.

The advantages of probabilistic models like ***Markov Chain Models*** are:

- Better extrapolation capabilities
- It can be easily integrated into dynamic BMS optimization processes
- The prediction of individual bridges' deterioration is much more efficient by probabilistic Markov Chain Models than traditional statistical models.

Notable points of this project:

- Updated deterioration models that were deterministic at first to probabilistic.
- They were developing regression methods for the historical condition rating data characteristics, resulting in probabilistic deterioration modeling.
- These models include transition probability matrices that account for the effects of design, geographic and functional characteristics on deterioration rates over different condition ratings.
- This advanced model was found to fit the historical condition rating data best and provide a unique insight into factors influencing deterioration over each bridge component's life-cycle.
- A simplified implementation of the probabilistic deterioration model achieved similar performance without rigorously incorporating external factors' effects on deterioration rates.
- To generate this equation to predict bridge-related crashes, a statistical analysis of bridge-related crashes was performed to correlate crash frequency with bridge design, functional, and safety characteristics.

Points that could be useful for other projects:

- Deterministic deterioration models may be a helpful starting point using RIS tasks, which can eventually be developed into a stochastic approach.

- Regression modes can be based on the historical condition rating data characteristics and then combined with RIS variables and uncertainties (e.g. task completion, task completion timing, task completion quality) to create a probabilistic model to predict the future condition ratings.
- A simplified implementation of the probabilistic deterioration models can be beneficial for future use with RIS as it is can be similarly effective without extensive data application.

Estimating the Future Condition of Highway Bridge Components Using National Bridge Inventory Data (Illinois)

The accurate prediction of the future condition of bridge components is an integral part of any BMS. Past bridge inspection data, along with information on any repair and retrofit, can provide a baseline for predicting future conditions of bridge components. As expected, such data are subject to relatively considerable uncertainty, primarily due to the inspection process variation. This uncertainty is also caused by unrecorded repairs or replacements conducted on various parts of the bridge. If not adequately considered in the bridge data analysis, the uncertainty may result in an erroneous prediction for future bridge conditions. To develop a reasonable estimate for future bridge conditions, there are two possible methods. In these methods, discrepancies inherent in bridge condition ratings that may have been due to unrecorded improvement works are removed to arrive at more consistent estimates for future bridge conditions. In one method, the adjustment in condition ratings is based on evidence of improvement work; the condition rating cannot be larger than previous ratings. In the other method, the duration between consecutive inspections is used to construct deterioration curves. These methods are applied to rating data collected from 2,601 Illinois bridges from 1976 to 1998.

Notable points in this project:

- Consistent condition rating of the bridges is considered to determine the deterioration of the bridges.
- If the historical condition rating data are not consistent (any condition rating is higher than the previous year's condition rating), that is omitted.
- In other methods, deterioration curves between successive inspections are considered to see how the bridge behaves between maintenance works. The duration between inspections will be used for the deterioration curves.
- The condition rating adjustments are based on evidence of improvement, and the updated condition rating cannot be larger than the previous condition rating.

Bridge Deterioration Models and Rates for the Caltrans Division of Research, Innovation, and System Information (California)

Caltrans was seeking knowledge from other state departments of transportation, vendors, and consultants regarding bridge deterioration modeling and rates. A developed survey model was sent to numerous points of contact, and 29 state DOT's, two vendors, and a consultant responded with their insight. System description, modeling practice and analysis, research implementation, and system assessment and analysis were all areas of the topic within the distributed survey. The AASHOTWare Bridge Management (BrM) modeling product was most cited as a primary resource and application by the state DOT's.

Several agencies were able to adjust their modeling applications to account for the most frequently chosen parameters: age, condition rating, superstructure material type, and use of deck overlays. Ten of the state DOT's account for maintenance treatments in their modeling application. This can be directly applicable to the NHDOT's RIS tasks and activities. Thirteen of the surveyed agencies described how the bridge modeling had changed asset management practices, including budgeting, project prioritization, preservation, and rehabilitation. A developed bridge deterioration modeling program for the NHDOT can benefit the organization within these categories when applied.

Specific notable points in this project:

This project is essentially a summary of the analysis completed following a nationwide distributed survey. The detailed findings in this report can help in finding a method of deterioration modeling suitable for NHDOT, given current use of RIS. The noted survey responses can also assist in choosing specific bridge elements or tasks to include within the projected bridge modeling tool, many, or all of which can be taken from the RIS.

Implementation of the 2013 AASHTO Manual for Bridge Element Inspection (2016)

The Florida DOT pursued implementing a new element inspection process using the Visual Element Migrator from AASHTO. This Migrator uses the CoRe Element inspections from Pontis and converts them to a format compatible with the 2013 Element Manual to use in the BMS. The approach to convert the element data from one format to another was chosen based on expert judgment. Before the migration, the data needed to be appropriately assessed and gathered.

Numerous files were being collected for this migration:

- Element definitions under the 2008 FDOT manual. These element definitions have been the basis of all inspections.
- Element definitions under the 2014 FDOT manual. The most common elements were chosen and carried into the new format. The "defects" or elements noted under certain circumstances were removed from the set.
- Inspection visit records for each bridge. For the present analysis, only the most recent year is needed.
- Element inspection records associated with the most recent inspections.
- Element inspection records from the Migrator program.

Element groupings were decided upon and selected based on the groupings of condition ratings of similar elements. However, some of the element conditions were based on selecting five condition states or three condition states. The CoRe elements with condition state not equal to four needed to be merged or divided to reach the equivalent four condition states.

Action effectiveness was also analyzed using the 2010 and 2015 manuals, and the element inspection data and maintenance work accomplished records. Each action subcategory (e.g., Rehab deck, clean rebar, and patch, repair joint…) was given a probability for each condition state after this action has taken place. These 2010 action subcategories were converted to the 2015 condition states.

Specific notable points in this project:

- Several element definitions and condition sets merged to form one dataset to transfer into a Migrator application quickly.
- The migration probability matrix was developed based on expert judgment.

- Once a few years of inspections are completed using the new program, a better approach will be possible.

Points that could be useful in other projects:

- The method of migration for both the element definitions and the element conditions will be useful to apply to deterioration modeling for RIS tasks at NHDOT
- If desired, this element migration can be replicated for NHDOT inspection and condition ratings
- The action effectiveness model can be applied to the RIS tasks and can better expand the RIS task list to analyze the maintenance, rehabilitation, and preservation actions.
- The condition states mentioned in the table below were pulled from the NHDOT Annual Report for 2018. These four condition ratings and their qualifications can act as the preliminary condition states used for data collection.

Condition State	**Description of Defects (Highway)**	**Description of Defects (Non-Highway)**
1 (Green)	All bridges carrying highway traffic that have all major structural elements with an NBIS rating equal to or greater than "7 = Good."	All non-highway bridges used as pedestrian, recreational, railroad, etc., crossings that have all major structural elements with an NBIS rating equal to or greater than "7 = Good".
2 (Yellow)	All bridges carrying highway traffic that have their lowest rated major structural element with an NBIS condition rating of "5 = Fair" or "6 = Satisfactory".	All non-highway bridges used as pedestrian, recreational, or railroad crossings that have their lowest rated major structural element with an NBIS condition rating of "5 = Fair" or "6 = Satisfactory".
3 (Red)	All bridges carrying highway traffic that have one or more major structural elements with an NBIS condition rating of "4 = Poor" or less. These bridges comprise the state/municipal Red Lists.	All non-highway bridges used as pedestrian, recreational, or railroad crossings that have one or more major structural elements with an NBIS rating of "4 = Poor" or less. These bridges comprise the corresponding Red List.
4 (Closed, N/A)	All bridges carrying highway traffic that have been closed due to one or more major structural elements with an NBIS rating equal to or less than "1 = Closed".	All non-highway bridges used as pedestrian, recreational, or railroad crossings that have been closed due to one or more of their major structural elements with an NBIS rating equal to or less than "1 = Closed"

Additional useful points for NHDOT:

Below are some potentially useful points taken from the literature review of projects related to DOT bridge deterioration modeling.

- It is possible to leverage existing data (county, tiers, bridge age) to develop deterioration curves for bridges and their components.
- RIS adherence could be used to develop deterioration curves in categories of bridges, for example: bridges that have not had any RIS tasks completed, bridges with lower amounts of RIS tasks completed, bridges that have gone through a significant amount of RIS work, and bridges that are replaced.
- RIS adherence of the expected date of task completion could be used as an input for deterioration modeling, like projects that used observed bridge performance in the duration between inspection and maintenance.
- Bridge historical condition rating data can be combined with recorded RIS tasks and their associated uncertainties to develop deterioration rates and probabilistic deterioration models for an entire bridge, or its components.

References

2018_stated_owned_red_list_bridges. Pdf." Accessed February 24, 2020. https://www.sandown.us/sites/sandownnh/files/uploads/2018_stated_owned_red_list_bridges.pdf

Blackwood, Rosalind, and Claire Currie. "The Use of Delphi Methods." Health Knowledge, 2016 2009. https://www.healthknowledge.org.uk/public-health-textbook/research-methods/1c-health-care-evaluation-health-care-assessment/use-delphi-methods.

Bolukbasi, et al. 2002. "Estimating the Future Condition of Highway Bridge Components Using National Bridge Inventory Data." Practice Periodical on Structural Design and Construction /Volume 9 Issue 1 - February 2004.

Bridge Detail Sheets | Document Library | Bridge Design | NH Department of Transportation. Accessed February 26, 2020. https://www.nh.gov/dot/org/projectdevelopment/bridgedesign/detailsheets/index.htm.

Bridge_summary.Pdf. Accessed February 20, 2020. https://www.nh.gov/dot/org/projectdevelopment/bridgedesign/documents/bridge_summary.pdf.

Bu et al 2012. "Performance Prediction of Concrete Elements in Bridge Substructures using Integrated Deterioration Method." Innovative Infrastructure – Toward Human Urbanism.

Cavalline, Tara L. et al 2014. "Determination of Bridge Deterioration Models and User Costs for NCDOT Bridge Management System." NCDOT Research Project Number 2014-07. https://connect.ncdot.gov/projects/research/pages/ProjDetails.aspx?ProjectID=2014-07

CTC & Associates LLC. "Bridge Deterioration Models and Rates." Preliminary Investigation. Caltrans Division of Research, Innovation and System Information, September 29, 2020. https://dot.ca.gov/-/media/dot-media/programs/research-innovation-system-information/documents/preliminary-investigations/pi-0274-a11y.pdf.

Danielson and Ekenberg, "Trade-Offs for Ordinal Ranking Methods in Multi-Criteria Decisions."

Dechev, N. "Lecture 7: Decision Making." The University of Victoria-Dept. of Mechanical Engineering, n.d. https://www.engr.uvic.ca/~mech350/Lectures/MECH350-Lecture-7.pdf.

Devault, Gigi. "How to Conduct a Delphi Survey." the balance: small business, December 21, 2018. https://www.thebalancesmb.com/how-to-conduct-a-delphi-survey-2297116.

FHWA 2014. "Specification for the National Bridge Inventory Bridge Elements." US Department of Transportation Federal Highway Administration.

Fink-Hafner, Danica, Tamara Dagen, May Doušak, Meta Novak, and Mitja Hafner-Fink. "Delphi Method: Strengths and Weaknesses" 16, no. 2 (2019): 1–19.

Hesse, Alex A., Rebecca A. Atadero, and Mehmet E. Ozbek. "Using Expert Opinion to Quantify Uncertainty in and Cost of Using Nondestructive Evaluation on Bridges." Edited by Deodato Tapete. *Advances in Civil Engineering* 2017 (July 19, 2017): 7925193. https://doi.org/10.1155/2017/7925193.

Johnson, Joshua F. 2012. "Determining the Items that Structure Bridge Management Components and their Relative Weights." Thesis. Colorado State University.

Kunsch, Pierre. (2019). A CRITICAL ANALYSIS ON RANK- ORDER-CENTROID (ROC) AND RANK- SUM (RS) WEIGHTS IN MULTICRITERIA-DECISION ANALYSIS VUB -BUTO Working Document June 2019 A critical analysis on Rank-Order-Centroid (ROC) and Rank-Sum (RS) weights in Multicriteria-Decision Analysis.

Lescauskiene, I.; Bausys, R.; Zavadskas, E.K.; Juodagalviene, B. VASMA Weighting: Survey-Based Criteria Weighting Methodology that Combines ENTROPY and WASPAS-SVNS to Reflect the Psychometric Features of the VAS Scales. *Symmetry* **2020**, *12*, 1641. https://doi.org/10.3390/sym12101641

LTBP InfoBridge - Data. Accessed February 20, 2020. https://infobridge.fhwa.dot.gov/Data#!#OverviewTab.

Morcous, G. and Hatami, A. 2011. "Developing Deterioration Models for Nebraska Bridges." Final Reports & Technical Briefs from Mid-America Transportation Center. University of Nebraska – Lincoln.

National Academies of Sciences, Engineering, and Medicine 2018. *Quantifying the Effects of Preservation Treatments on Pavement Performance*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25298.

NHDOT "Bridgeprogramrecommendedinvestmentstrategy.Pdf." Accessed February 24, 2020. https://www.nh.gov/dot/org/projectdevelopment/bridgedesign/documents/bridgeprogramrecommendedinvestmentstrategy.pdf.

NHDOT, 2018. "NHDOT Bridge Condition and Bridge Program – Annual Report 2018." "2018-Annualreport-Bridgeconditionandbridgeprogram.Pdf." Accessed February 20, 2020. https://www.nh.gov/dot/org/projectdevelopment/bridgedesign/documents/2018-annualreport-bridgeconditionandbridgeprogram.pdf.

NYSDOT. (2014). Transportation asset management plan draft v 05-02-14. Retrieved from: http://www.tamptemplate.org/wp-content/uploads/tamps/023_newyorkstatedot.pdf

Odu, Godwin. (2019). Weighting methods for multi-criteria decision making technique. Journal of Applied Sciences and Environmental Management. 23. 1449. 10.4314/jasem.v23i8.7.

Rashidi, M. and Gibson, P. 2012. "A methodology for bridge condition evaluation." Journal of Civil Engineering and Architecture, 6 (9), 1149-1157.

Roszkowska, Ewa. (2013). Rank Ordering Criteria Weighting Methods – A Comparative Overview. Optimum.Studia Ekonomiczne. Nr 5 (65. 14-33. 10.15290/ose.2013.05.65.02.

Sobanjo, John O. 2011. "State transition probabilities in bridge deterioration based on Weibull sojourn times, Structure and Infrastructure Engineering," 7:10, 747-764, DOI: 10.1080/15732470902917028

Sobanjo, John O., and Thompson, Paul D. 2016. "Implementation of the 2013 AASHTO Manual for Bridge Element Inspection." Final Report for State Maintenance Office, Florida Department of Transportation.

Valentin. "Weighted Decision Matrix." Blog. airfocus, February 26, 2020. https://airfocus.com/blog/weighted-decision-matrix-prioritization/.

Appendix A

NHDOT Bridge Program Recommended Investment Strategy (RIS), dated July 2018.

1

NHDOT Bridge Program Recommended Investment Strategy

Approved By: ____________________ Date: July 31, 2018
L. Robert Landry, PE
Chair, NHDOT Bridge Management Committee

July 23, 2018 NHDOT Bridge Program – Recommended Investment Strategy

NHDOT Bridge Program Recommended Investment Strategy

Introduction

The NHDOT Bridge Management Committee (BMC) has developed Recommended Investment Strategies (RIS) for all five bridge types (girder, truss, moveable, timber, and culvert). The goal of these schedules is to maximize the service life and minimize the life cycle costs of New Hampshire bridges so they can continue to remain in service and provide an efficient transportation network.

Like most structures, bridges last longer when timely investments are made at prescribed intervals for needed maintenance, preservation, and rehabilitation activities. To appropriately apply these efforts, schedules have been developed for specific activities that, through experience, are shown to extend the service life of each type of bridge. Consequently, appropriate funding levels are required for these activities to be performed in accordance with the schedules developed for each type of bridge. These schedules were based on data compiled from past efforts, the issues or concerns associated with each activity, and the overall knowledge and experience of the BMC and supporting staff.

These strategies are used to develop estimated system-wide levels of investment for the overall Bridge Program and are not specific for individual bridge investments. Costs to perform these activities on individual bridges can vary considerably based on a number of site-specific factors. Thus, the information presented herein should only be used for system-wide funding recommendations. The RIS also assumes that the recommended actions have been made on all bridges to date, which is not the case, especially with the older bridges in the inventory. It also assumes that the ages of each type of bridge are distributed uniformly throughout the life cycle of each bridge type, which again is not the case. However, these are necessary assumptions for developing these recommended work schedules and funding levels.

As shown in the tables below (December 31, 2017 data), the girder bridge is the dominant structure type for all ownership groups, particularly State-owned bridges. Please note that this data includes only the NH-owned deck area of bridges that are shared with adjoining states.

Data for State (non-Turnpike) bridges by Bridge Type

Bridge Type	Count	Deck Area (sq. ft.)*	Percentage By Deck Area
Girder	1,147	6,528,490	83.6%
Truss	39	217,654	2.8%
Moveable	4	121,474	1.5%
Timber	38	52,714	0.7%
Culvert	762	888,320	11.4%
Totals:	**1,990**	**7,808,653**	**100%**

Data for State Turnpike bridges by Bridge Type

Bridge Type	Count	Deck Area (sq. ft.)*	Percentage By Deck Area
Girder	147	2,121,468	90.9%
Truss	2	118,781	5.1%
Moveable	0	0	0.0%
Timber	0	0	0.0%
Culvert	22	92,414	4.0%
Totals:	**171**	**2,332,663**	**100%**

Data for Municipally (and Other) bridges by Bridge Type

Bridge Type	Count	Deck Area (sq. ft.)*	Percentage By Deck Area
Girder	709	1,746,292	68.0%
Truss	37	172,051	6.7%
Moveable	0	0	0.0%
Timber	221	208,007	8.1%
Culvert	721	440,149	17.2%
Totals:	**1,688**	**2,566,499**	**100%**

Data for all bridges by Bridge Type

Bridge Type	Count	Deck Area (sq. ft.)*	Percentage By Deck Area
Girder	2,003	10,396,250	81.8%
Truss	78	508,486	4.0%
Moveable	4	121,474	1.0%
Timber	259	260,721	2.0%
Culvert	1,505	1,420,884	11.2%
Totals:	**3,849**	**12,707,815**	**100%**

* Includes NH portion only of bridge deck areas for bridges shared with adjoining states.

(I) Analysis

As can be seen from the above data, girder bridges represent the largest number of bridges throughout the state, and thus have the greatest effect on where the available bridge funds are applied. Investment strategies and schedules for recommended work activities to be performed on girder bridges were then developed for two life cycles: 80-years and 120-years. The costs for these activities over the different life cycles were then compared and evaluated. The results indicated that the schedule for the 120-year life cycle ($8.10 per year per sq. ft.) was about 15% more economical than the schedule for the 80-year life cycle ($9.60 per year per sq. sf.), with the difference being $1.50 per year per sq. ft. (See Appendix "A" and Appendix "B" for information on development of these life cycle schedules.)

It would be appropriate to review and update the Recommended Investment Strategy for each type of bridge every five (5) years to ensure that current data is used as the basis for Bridge Program funding recommendations. A comparison of the work activities and associated costs for the different investment schedules and life cycles could demonstrate whether the goals of cost savings and an overall increase in the longevity of the state's bridges are being attained.

(II) Typical Bridge Recommend Investment Strategy

The value of bridges in New Hampshire to our citizens, visitors, and economy cannot be overstated. The connectivity they provide to the local communities, as well as their contribution to the effectiveness of the transportation system could be considered irreplaceable on a statewide scale. The cost to replace every bridge in New Hampshire (state and municipal) would easily amount to billions of dollars. For this reason, the tremendous investment made in the past to construct these bridges must be protected so that they remain safe and available for use by the traveling public.

For the bridge owner (state or municipalities) to protect this investment and ensure that it can provide safe and continual service, a schedule for routine work activities should be followed for each bridge in their inventory. It is recognized that schedules for work activities for individual bridges will vary depending on the type of bridge and the site-specific factors, such as traffic volume, topography, streamflow, etc.

Tables 1 through 5 present the recommended schedule of work activities for each bridge type.

(A) Girder Bridges include the following classifications of bridges:

• BAIB – Bailey or similar bridge	• Jack – Jack Arch Concrete on I-Beams
• BGB – Beam Girder Bridge	• NEBT – Prestressed Bulb Tee
• CS – Concrete Slab	• NEXT – Northeast Extreme Tee
• CTB – Concrete Tee Beam	• PBB – Prestressed Butted Boxes
• DPG – Deck Plate Girder	• PIB – Prestressed I-Beams
• IB – I Beams without Deck	• PSB – Prestressed Spread Boxes
• IB-BP – I Beams with Bridge Plank	• PSC – Prestressed Concrete
• IB-C – I Beams with Concrete Deck	• PTB – Prestressed Tee Beams
• IB-G – I Beams with Steel Grid	• PVS – Prestressed Voided Slabs
• IB-S – I Beams with Steel Plate	• SRF – Steel Rigid Frame
• INVER – Inverset I-Beam/Concrete	• TPG – Thru Plate Girder

Table 1: Recommended Schedule of Work Activities for Girder Bridges

Year (Frequency)	Work Effort/Activity	Category of Work	Responsible Bureau
Annually	Clean and Seal; Clear Debris	Maintenance	Bridge Maintenance
5	Crack Seal Pavement	Preservation	Highway Design
10	Pavement Inlay	Preservation	Highway Design
15	Crack Seal Pavement	Preservation	Highway Design
20	Patch Deck and Substructure; Replace Membrane, Pavement, & Expansion Joints; Rehab Bearings; Touch Up Paint (if applicable)	Preservation	Bridge Design
25	Crack Seal Pavement	Preservation	Highway Design
30	Pavement Inlay	Preservation	Highway Design
35	Crack Seal Pavement	Preservation	Highway Design
40	Patch Deck and Substructure; Replace Membrane, Pavement, & Expansion Joints; Rehab Bearings; Touch Up Paint (if applicable)	Preservation	Bridge Design
45	Crack Seal Pavement	Preservation	Highway Design
50	Pavement Inlay	Preservation	Highway Design
55	Crack Seal Pavement	Preservation	Highway Design
60	Replace Deck, Membrane, Pavement, & Joints; Replace Bearings; Patch Substructure, New Paint (if applicable)	Rehabilitation	Bridge Design
65	Crack Seal Pavement	Preservation	Highway Design
70	Pavement Inlay	Preservation	Highway Design
75	Crack Seal Pavement	Preservation	Highway Design
80	Patch Deck and Substructure; Replace Membrane, Pavement, & Expansion Joints; Rehab Bearings; Touch Up Paint (if applicable)	Preservation	Bridge Design
85	Crack Seal Pavement	Preservation	Highway Design
90	Pavement Inlay	Preservation	Highway Design
95	Crack Seal Pavement	Preservation	Highway Design
100	Patch Deck and Substructure; Replace Membrane, Pavement, & Expansion Joints; Rehab Bearings; Touch Up Paint (if applicable)	Preservation	Bridge Design
105	Crack Seal Pavement	Preservation	Highway Design
110	Pavement Inlay	Preservation	Highway Design
115	Crack Seal Pavement	Preservation	Highway Design
120	Replace Bridge (or superstructure)	Replacement	Bridge Design

(B) Truss Bridges include the following classifications of bridges:

• DT – Deck Truss
• HT – High Truss
• LT – Low Truss
• SA – Steel Arch

Table 2: Recommended Schedule of Work Activities for Truss Bridges:

Year (Frequency)	Work Effort/Activity	Category of Work	Responsible Bureau
Annually	Clean and Seal; Clear Debris	Maintenance	Bridge Maintenance
5	Crack Seal Pavement	Preservation	Highway Design
10	Pavement Inlay	Preservation	Highway Design
15	Crack Seal Pavement	Preservation	Highway Design
20	Patch Deck and Substructure; Replace Membrane, Pavement, and Expansion Joints; Rehabilitate Bearings; Structural steel repairs; Touch Up Paint (if applicable)	Preservation	Bridge Design
25	Crack Seal Pavement	Preservation	Highway Design
30	Pavement Inlay	Preservation	Highway Design
35	Crack Seal Pavement	Preservation	Highway Design
40	Patch Deck and Substructure; Replace Membrane, Pavement, and Expansion Joints; Rehabilitate Bearings; Structural steel repairs; Touch Up Paint (if applicable)	Preservation	Bridge Design
45	Crack Seal Pavement	Preservation	Highway Design
50	Pavement Inlay	Preservation	Highway Design
55	Crack Seal Pavement	Preservation	Highway Design
60	Replace Deck; Patch Substructure; Replace Membrane, Pavement, and Expansion Joints; Replace Bearings; Structural steel repairs; New Paint (if applicable)	Rehabilitation	Bridge Design
65	Crack Seal Pavement	Preservation	Highway Design
70	Pavement Inlay	Preservation	Highway Design
75	Crack Seal Pavement	Preservation	Highway Design
80	Patch Deck and Substructure; Replace Membrane, Pavement, and Expansion Joints; Rehabilitate Bearings; Structural steel repairs; Touch Up Paint (if applicable)	Preservation	Bridge Design
85	Crack Seal Pavement	Preservation	Highway Design
90	Pavement Inlay	Preservation	Highway Design
95	Crack Seal Pavement	Preservation	Highway Design
100	Replace Bridge (or superstructure)	Replacement	Bridge Design

(C) Moveable Bridges include two very different types of moveable structures: bascule and vertical lift. These different moveable bridges require very different work tasks and treatments for their maintenance, preservation, and rehabilitation.

(C-1) Bascule Moveable Bridges include the following classification of bridges:

- BAS – Bascule Span

Table 3.1: Recommended Schedule of Work Activities for Bascule Moveable Bridges:

Year (Frequency)	Work Effort/Activity	Category of Work	Responsible Bureau
Annually	Clean & Seal Substructure; Clear Debris, Electrical & Mechanical Tasks	Maintenance	Bridge Maintenance
5	Crack Seal Pavement	Preservation	Highway Design
10	Pavement Inlay	Preservation	Highway Design
15	Crack Seal Pavement	Preservation	Highway Design
20	Pavement Inlay	Preservation	Highway Design
25	Patch Deck and Substructure; Replace Membrane, Pavement, & Expansion Joints; Structural steel repairs; Touch Up Paint (if applicable) Electrical & Mechanical R&R; Replace Gates; Rehabilitate Fenders;	Preservation	Bridge Design
30	Crack Seal Pavement	Preservation	Highway Design
35	Pavement Inlay	Preservation	Highway Design
40	Crack Seal Pavement	Preservation	Highway Design
45	Pavement Inlay	Preservation	Highway Design
45	Crack Seal Pavement	Preservation	Highway Design
50	Replace Deck; Patch Substructure; Replace Membrane, Pavement, & Expansion Joints; Structural steel repairs; Complete Paint Removal/Application (if applicable); Replace Bearings; Electrical & Mechanical R&R; Replace Gates; Rehabilitate Fenders;	Rehabilitation	Bridge Design
55	Crack Seal Pavement	Preservation	Highway Design
60	Pavement Inlay	Preservation	Highway Design
65	Crack Seal Pavement	Preservation	Highway Design
70	Pavement Inlay	Preservation	Highway Design
75	Patch Deck and Substructure; Replace Membrane, Pavement, & Expansion Joints; Structural steel repairs; Touch Up Paint (if applicable) Electrical & Mechanical R&R; Replace Gates; Rehabilitate Fenders;	Rehabilitation	Bridge Design
80	Crack Seal Pavement	Preservation	Highway Design
85	Pavement Inlay	Preservation	Highway Design
90	Crack Seal Pavement	Preservation	Highway Design
95	Pavement Inlay	Preservation	Highway Design
100	Replace Bridge (or superstructure)	Replacement	Bridge Design

(C-2) Vertical Lift Moveable Bridges include the following classification of bridges:

- LIFT – Vertical Lift

Table 3.2: Recommended Schedule of Work Activities for Moveable Bridges:

Year (Frequency)	Work Effort/Activity	Category of Work	Responsible Bureau
Annually	Clean & Seal Substructure; Clear Debris, Electrical & Mechanical Tasks	Maintenance	Bridge Maintenance
5	Crack Seal Pavement	Preservation	Highway Design
10	Pavement Inlay	Preservation	Highway Design
15	Crack Seal Pavement	Preservation	Highway Design
20	Pavement Inlay	Preservation	Highway Design
25	Patch Deck and Substructure; Replace Membrane, Pavement, & Expansion Joints; Structural steel repairs; Touch Up Paint (if applicable) Replace Lift Ropes; Replace Counterweight Ropes; Electrical & Mechanical R&R; Replace Gates; Rehabilitate Fenders;	Preservation	Bridge Design
30	Crack Seal Pavement	Preservation	Highway Design
35	Pavement Inlay	Preservation	Highway Design
40	Crack Seal Pavement	Preservation	Highway Design
45	Pavement Inlay	Preservation	Highway Design
45	Crack Seal Pavement	Preservation	Highway Design
50	Replace Deck; Patch Substructure; Replace Membrane, Pavement, & Expansion Joints; Structural steel repairs; Complete Paint (if applicable); Replace Bearings; Replace Lift Ropes; Replace Counterweight Ropes; Electrical & Mechanical R&R; Replace Gates; Rehabilitate Fenders;	Rehabilitation	Bridge Design
55	Crack Seal Pavement	Preservation	Highway Design
60	Pavement Inlay	Preservation	Highway Design
65	Crack Seal Pavement	Preservation	Highway Design
70	Pavement Inlay	Preservation	Highway Design
75	Patch Deck and Substructure; Replace Membrane, Pavement, & Expansion Joints; Structural steel repairs; Touch Up Paint (if applicable) Replace Lift Ropes; Replace Counterweight Ropes; Electrical & Mechanical R&R; Replace Gates; Rehabilitate Fenders;	Rehabilitation	Bridge Design
80	Crack Seal Pavement	Preservation	Highway Design
85	Pavement Inlay	Preservation	Highway Design
90	Crack Seal Pavement	Preservation	Highway Design
95	Pavement Inlay	Preservation	Highway Design
100	Replace Bridge (or superstructure)	Replacement	Bridge Design

(D) Timber Bridges include the following classifications of bridges:

• CTC – Concrete Timber Composite
• IB-W – I-Beams with Wood Deck
• TB – Timber Bridge
• TB-C – Covered Bridge
• TB-CS – Timber Bridge Concrete Slab
• TS – Timber Slab
• TS-P – Prestressed Timber Slab

Table 4: Recommended Schedule of Work Activities for Timber Bridges

Year (Frequency)	Work Effort/Activity	Category of Work	Responsible Bureau
Annually	Clean and Seal Substructure; Clear Debris	Maintenance	Bridge Maintenance
5	Crack Seal Pavement (Paved timber decks only)	Preservation	Highway Design
10	Pavement Inlay (Paved timber decks only) Patch/Repair Deck and Substructure;	Preservation	Highway Design Bridge Maintenance
15	Crack Seal Pavement (Paved timber decks only)	Preservation	Highway Design
20	Replace Timber Deck; Repair Substructure; Replace Membrane & Pavement; (Paved timber decks only) Repair Expansion Joints; Rehabilitate Bearings; Rehabilitate Timbers;	Preservation	Bridge Design
25	Crack Seal Pavement (Paved timber decks only)	Preservation	Highway Design
30	Pavement Inlay (Paved timber decks only) Patch/Repair Deck and Substructure;	Preservation	Highway Design Bridge Maintenance
35	Crack Seal Pavement (Paved timber decks only)	Preservation	Highway Design
40	Replace Timber Deck; Repair Substructure; Replace Membrane & Pavement; (Paved timber decks only) Replace Expansion Joints; (if applicable) Replace Bearings; Rehabilitate Timbers;	Preservation	Bridge Design
45	Crack Seal Pavement (Paved timber decks only)	Preservation	Highway Design
50	Pavement Inlay (Paved timber decks only) Patch/Repair Deck and Substructure;	Preservation	Highway Design Bridge Maintenance
55	Crack Seal Pavement (Paved timber decks only)	Preservation	Highway Design
60	Replace Timber Deck; Repair Substructure; Replace Membrane & Pavement; (Paved timber decks only) Repair Expansion Joints; Rehabilitate Bearings; Rehabilitate Timbers;	Preservation	Bridge Design
65	Crack Seal Pavement (Paved timber decks only)	Preservation	Highway Design
70	Pavement Inlay (Paved timber decks only) Patch/Repair Deck and Substructure;	Preservation	Highway Design Bridge Maintenance
75	Crack Seal Pavement (Paved timber decks only)	Preservation	Highway Design
80	Replace bridge (or superstructure)	Replacement	Bridge Design

It is recognized that there are 48 covered bridges in New Hampshire (7 state; 41 municipal), however, the activities and funds needed to address deficiencies in these historic structures present unique challenges as they are much more complex than other timber bridges.

It is also recognized that very few timber bridges have paved decks and even fewer also have waterproofing membrane applied. The anticipated costs needed to perform the membrane and pavement work indicated above represents a small portion of the total estimated costs presented for timber bridges.

(E) Culvert Bridges include two very different types of structures: reinforced concrete (including masonry) and metal (steel and aluminum). These different materials require very different work tasks and treatments for their maintenance, preservation, and rehabilitation.

Of the total number of state and municipal culverts (metal or concrete) in the inventory, the majority (90%±) cross waterways. For this reason, these culverts would likely require preservation work due to the wear on the culvert invert from water flow and any debris or cobbles carried through them over time. The remaining 10%± of the total number of culverts are for recreational or other uses, and thus do not cross a waterway, would not experience the same wear, and would not require the same maintenance and work activities.

In addition, concrete culverts that are set "at grade" and are not completely buried will also require maintenance work to crack seal the pavement or to install a pavement in-lay, similar to the maintenance work indicated for bridges with concrete decks.

It is further recognized that metal (steel or aluminum) culverts that cross waterways often have a much reduced life span, sometimes much less than the 60-year service life anticipated for other culverts. For this reason, Bridge Design no longer allows metal (steel) sections of culverts to be installed below anticipated high water levels for waterway crossings.

(E-1) Metal Culvert Bridges include the following classifications of bridges:

• MP – Metal Pipe
• MP-A – Metal Plate Arch
• MP-B – Metal Plate Box Culvert

Table 5.1: Recommended Schedule of Work Activities for Metal Culvert Bridges:

Year (Frequency)	Work Effort/Activity	Category of Work	Responsible Bureau
Annually	Clean and Seal Substructure, Clear Debris	Maintenance	Bridge Maintenance
10	Install or Repair Invert (Waterway culverts only)	Preservation	Bridge Maintenance
20	Repair Invert (Waterway culverts only)	Preservation	Bridge Maintenance
30	Repair Invert (Waterway culverts only)	Preservation	Bridge Maintenance
40	Repair Invert (Waterway culverts only)	Preservation	Bridge Maintenance
50	Repair Invert (Waterway culverts only)	Preservation	Bridge Maintenance
60	Replace Culvert	Replacement	Bridge Design

(E-2) Concrete and Masonry Culvert Bridges include the following classifications of bridges:

• CA – Concrete Arch	• CPP – Concrete Polymer Pipe
• CACUL – Concrete Arch Culvert	• CRF – Concrete Rigid Frame
• CAR – Concrete Arch Rib	• CRF-P – Concrete Rigid Frame-Precast
• CB – Concrete Box	• MA – Masonry Arch
• CB-P – Concrete Box - Precast	• MA-CA – Masonry and Conc. Arch
• CP – Concrete Pipe	• MS – Masonry Slab

Table 5.2: Recommended Schedule of Work Activities for Concrete and Masonry Culvert Bridges:

Year (Frequency)	Work Effort/Activity	Category of Work	Responsible Bureau
Annually	Clean and Seal Substructure, Clear Debris	Maintenance	Bridge Maintenance
5	Crack Seal Pavement (Required for at-grade structures only)	Preservation	Highway Design
10	Pavement Inlay (Required for at-grade structures only)	Preservation	Highway Design
15	Crack Seal Pavement (Required for at-grade structures only)	Preservation	Highway Design
20	Pavement Inlay (Required for at-grade structures only)	Preservation	Highway Design
25	Crack Seal Pavement (Required for at-grade structures only)	Preservation	Highway Design
30	Pavement Inlay (Required for at-grade structures only)	Preservation	Highway Design
35	Crack Seal Pavement (Required for at-grade structures only)	Preservation	Highway Design
40	Pavement Inlay (Required for at-grade structures only)	Preservation	Highway Design
45	Crack Seal Pavement (Required for at-grade structures only)	Preservation	Highway Design
50	Pavement Inlay (Required for at-grade structures only)	Preservation	Highway Design
55	Crack Seal Pavement (Required for at-grade structures only)	Preservation	Highway Design
60	Pavement Inlay (Required for at-grade structures only)	Preservation	Highway Design
65	Crack Seal Pavement (Required for at-grade structures only)	Preservation	Highway Design
70	Pavement Inlay (Required for at-grade structures only)	Preservation	Highway Design
75	Crack Seal Pavement (Required for at-grade structures only)	Preservation	Highway Design
80	Replace Culvert	Replacement	Bridge Design

(III) Summary Comparison

This report outlines the recommended activities and schedules to maintain, preserve, rehabilitate, or replace all bridge types (girder, truss, moveable, timber, and culvert) in New Hampshire. The information summarized in Appendices A & B presents a cost comparison, using cost data from 2017, of two different investment strategies for girder bridges.

Appendix "A" outlines the costs of only performing minimal bridge work resulting in an 80-year bridge service life, whereas Appendix "B" outlines the costs of performing all recommended bridge work resulting in a 120-year bridge service life:

- Appendix "A": Investment strategy resulting in an 80-year bridge service life = $9.61 per sq. ft.
- Appendix "B": Investment strategy resulting in a 120-year bridge service life = $8.10 per sq. ft.

Savings = $1.51 per sq. ft.

The cost of obtaining the 120-year bridge service life is $1.51 per sq. ft. less than the cost for obtaining the 80-year bridge service life which also requires bridge replacement 40 years sooner. This data supports the Recommended Investment Strategy presented herein that performing scheduled maintenance and preservation activities results in a 50% longer bridge service life at a 15.7% lower cost over the 120-year projected service life of the bridge, when compared to only performing rehabilitation and replacement activities over an 80-year bridge service life.

Similar cost comparisons can be made for the four remaining types of bridges confirming that performing specific tasks at scheduled time intervals is the more economical approach to obtaining a longer bridge service life. The result of this strategy is that bridges that receive scheduled work activities will consistently be in better condition and have a much longer service life than bridges on which no maintenance or scheduled work activities are performed.

Appendix "A": Investment Strategy and Schedule for Girder Bridge resulting in 80-year service life

Frequency (Year)	Work Activity	Category	Maintenance Cost/Sq. Ft.	Preservation Cost/Sq. Ft.	Rehabilitation Cost/Sq. Ft.	Replacement Cost/Sq. Ft.
Annual	Clean and seal	Maintenance	$ 0.10	-	-	-
5	Crack seal	Preservation	-	$ 0.07	-	-
10	Replace pavement	Preservation	-	$ 1.60	-	-
15	Crack seal	Preservation	-	$ 0.07	-	-
20	Replace pavement	Preservation	-	$ 1.60	-	-
25	Crack seal	Preservation	-	$ 0.07	-	-
30	Replace pavement	Preservation	-	$ 1.60	-	-
35	Crack seal	Preservation	-	$ 0.07	-	-
40	Replace deck, etc.	Rehabilitation	-	-	$ 100.00	-
45	Crack seal	Preservation	-	$ 0.07	-	-
50	Replace pavement	Preservation	-	$ 1.60	-	-
55	Crack seal	Preservation	-	$ 0.07	-	-
60	Replace pavement	Preservation	-	$ 1.60		-
65	Crack seal	Preservation	-	$ 0.07	-	-
70	Replace pavement	Preservation	-	$ 1.60	-	-
75	Crack seal	Preservation	-	$ 0.07	-	-
80	Replace bridge	Replacement	-	-	-	$ 650.00

Deck service life = 40 years **Bridge service life = 80 years**	Cost / Sq. Ft. over 80-year bridge life	$ 8.00	$ 10.16	$ 100.00	$ 650.00
	Cost / Sq. Ft.	$ 0.10	$ 0.13	$ 1.25	$ 8.13
Costs per year	Cost/Sq. Ft. per year for 80-year bridge life: **$9.61** =	Maintenance + ($ 0.10) +	Preservation. + ($ 0.13) +	Rehabilitation + ($ 1.25) +	Replacement ($ 8.13)

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Appendix "B": Investment Strategy and Schedule for Girder Bridge resulting in 120-year service life

Frequency (Year)	Work Activity	Category	Maintenance Cost/Sq. Ft.	Preservation Cost/Sq. Ft.	Rehabilitation Cost/Sq. Ft.	Replacement Cost/Sq. Ft.
Annual	Clean and seal	Maintenance	$ 0.10	-	-	-
5	Crack seal	Preservation	-	$ 0.07	-	-
10	Replace pavement	Preservation	-	$ 1.60	-	-
15	Crack Seal	Preservation	-	$ 0.07	-	-
20	Patch deck; Replace pavement, membrane, and expansion joints	Preservation	-	$ 50.00	-	-
25	Crack Seal	Preservation	-	$ 0.07	-	-
30	Replace Pavement	Preservation	-	$ 1.60	-	-
35	Crack seal	Preservation	-	$ 0.07	-	-
40	Patch deck; Replace pavement, membrane, and expansion joints	Preservation	-	$ 50.00	-	-
45	Crack seal	Preservation	-	$ 0.07	-	-
50	Replace pavement	Preservation	-	$ 1.60	-	-
55	Crack Seal	Preservation	-	$ 0.07	-	-
60	Replace deck, etc.	Rehabilitation	-	-	$ 100.00	-
65	Crack Seal	Preservation	-	$ 0.07	-	-
70	Replace pavement	Preservation	-	$ 1.60	-	-
75	Crack seal	Preservation	-	$ 0.07	-	-
80	Patch deck; Replace pavement, membrane, and expansion joints	Preservation	-	$ 50.00	-	-
85	Crack Seal	Preservation	-	$ 0.07	-	-
90	Replace pavement	Preservation	-	$ 1.60	-	-
95	Crack seal	Preservation	-	$ 0.07	-	-
100	Patch deck; Replace pavement, membrane, and expansion joints	Preservation	-	$ 50.00	-	-
105	Crack Seal	Preservation	-	$ 0.07	-	-
110	Replace pavement	Preservation	-	$ 1.60	-	-
115	Crack seal	Preservation	-	$ 0.07	-	-
120	Replace bridge	Replacement	-	-	-	$ 650.00

Deck service life = 60 years **Bridge service life = 120 years**	Cost / Sq. Ft. over 120-year bridge life	$ 12.00	$ 210.44	$ 100.00	$ 650.00
	Cost / Sq. Ft.	$ 0.10	$ 1.75	$ 0.83	$ 5.42
Costs per year	Cost/Sq. Ft. per year for 120-year bridge life: **$8.10** =	Maintenance + ($ 0.10) +	Preservation. + ($ 1.75) +	Rehabilitation + ($ 0.83) +	Replacement ($ 5.42)

End of Report