Significant Factors of Bridge Deterioration

Task 3 Report: Significant Factors and General Condition Rating Analysis

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1 Introduction

Task 3 of this research continues the statistical analysis from Task 2 using additional variables and bridge groups to improve the results from which the most significant factors were selected. These significant factors and bridge groups were used to run a General Condition Rating (GCR) analysis within the Bridge Management (BrM).

Section 2 of this Report summarizes the new reinforced concrete bridge deck group with different surface overlays (bituminous, epoxy, etc.) and Section 3 describes the new variables (e.g., rain and snow precipitation, freeze-thaw cycles, and deicer application data) added to the statistical analysis. A more-complete description of the original bridge groups and variables is found in the Task 2 report.

Section 4 summarizes the analysis methods used. The Generalized Linear Model (GLM) and Random Forest (RF) statistical analysis methods used are the same as those completed during Task 2. A General Condition Rating analysis within BrM is described in Section 5 followed by results in Section 6 and a discussion in Section 7. A summary of the Task 3 Report is included in Section 8.

The overall objective of Task 3 is to a) quantify the influence of the selected variables for predicting National Bridge Inventory (NBI) deck ratings, b) use the results as input variables for a GCR analyses, c) and explore alternatives to integrate the results within the larger BrM optimization framework.

2 Bridge Groups

There are a total of 5,074 bridges and culverts across the state of Montana that are maintained by the Montana Department of Transportation (MDT), county, city, and township agencies. The analysis focused specifically on 2,966 structures maintained by MDT that includes 2,232 bridges and 734 culverts. The state-maintained structures can be seen in Figure 1.

Bridge deck material is a new bridge group added to the statistical analysis. There are four types of deck materials identified in the structural asset data: concrete cast-in-place (n = 1,686), concrete precast panel (n = 39), corrugated steel (n = 3), and wood or timber (n = 344). Due to the low number of bridge decks made with precast concrete, corrugated steel, and the relatively low traffic volumes and maintenance expenditures on wood and timber bridges, the statistical analysis focused on bridges with concrete cast-in-place decks. The inclusion of reinforced concrete decks as a new bridge group results in different numbers of bridges in each group when compared to the statistical analysis used in Task 2. The new bridge numbers for each group are summarized below.

2.1 Maintenance Districts

Bridges were divided into maintenance districts to highlight the different environmental conditions across the state of Montana and specific effort put forward by each district. The number of bridges with reinforced concrete decks in each maintenance district are: Billings (n = 348), Butte (n = 420), Glendive (n = 287), Great Falls (n = 282), and Missoula (n = 349).

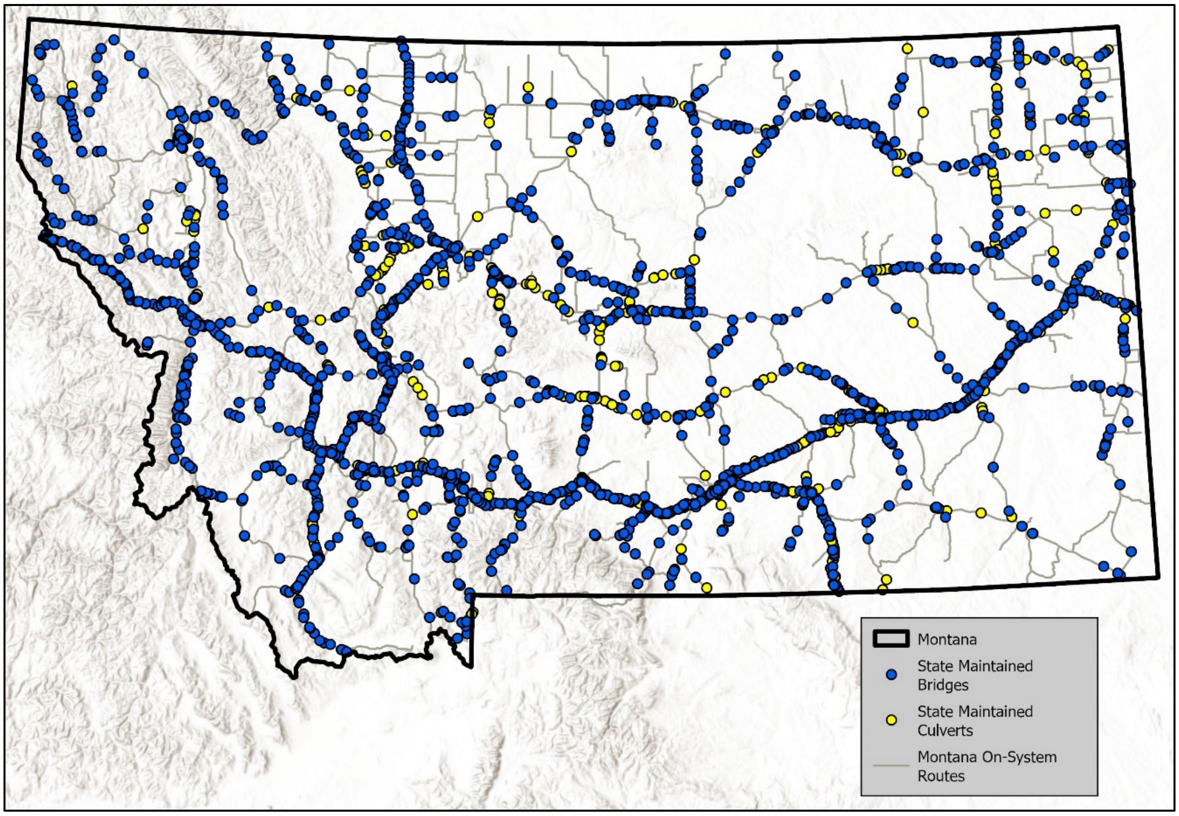

Figure 1: State maintained bridges and culverts in Montana.

2.2 Superstructure Materials

Bridge materials considered for the superstructure include concrete, steel, and wood. Out of the 1,686 bridges in the analysis, there are 1,366 made from concrete, 311 steel bridges, and 9 made from wood, or timber. Due to the low number of bridges with wood or timber superstructures, only concrete and steel superstructure materials were included in this analysis.

2.3 Functional Class

Bridges were also divided into functional class groups. Four types of road functional classes are identified in the MDT on-system routes: interstate (n = 799), major arterial (n = 237), minor arterial (n = 290), and collector roads (n = 360).

2.4 Bridge Deck Surface

The deck surface type is a new bridge group added to the Task 3 Report. Deck surfaces are intended to increase the life of the bridge deck and provide safer travel conditions, based on the type of surface applied. Five different surface type groups were considered for this analysis: bituminous (n = 210), epoxy overlay (n = 128), latex concrete or similar (n = 206), monolithic concrete (n = 814), and no additional surface (n = 311).

3 Model Variables

For the analysis described in this report, insignificant variables were removed from the Task 2 analysis (e.g., number of lanes, number of spans, urban area, deck material, NHS highways, and road surface type) because of their low statistical significance. Four additional variables were included in the analysis: freeze-thaw cycles, rain precipitation, snow precipitation, and deicer application rate. This results in 21 bridge variables that were used to predict NBI concrete bridge deck ratings. An updated summary of the 13 numerical variables can be seen in Table 1, and the eight categorical variables can be seen in Table 2. A description of the data used for the four new variables is described below.

Table 1: Summary of numeric data variables used in analysis.

Variable	Min.	Max.	Mean	Median	Std. Dev.
Age (yr)	1	102	46	51	18
Maximum Span Length (ft)	8	520	75	65	44
Total Structural Length (ft)	10	2,122	210	135	226
Deck Width (ft)	15	312	44	42	18
Deck Area (ft^2)	395	142,028	8,952	5,590	10,559
Average Annual Daily Traffic	0	40,211	5,177	3,141	6,080
Average Annual Daily Truck Traffic	0	3,651	632	155	815
Bridge Skew (degree)	0	99	10	0	14
Speed on Bridge (mph)	25	80	69	70	14
Average Freeze/Thaw Cycles (days)	5	187	116	118	30
Average Rain Precipitation (in)	0	43	14	13	7
Average Snow Precipitation (in)	0	169	10	6	17
Deicer Application (gal/ln-mi)	19	3,589	439	151	729

Table 2: Categorical variables used in the Task 3 analysis.

Variable	Number of Categories	Names in Categories
District	5	Billings, Butte, Glendive, Great Falls, Missoula
County	56	All 56 counties in Montana
Service Under Bridge	8	Creek, Drainage, Irrigation, Lake/Reservoir, Land, Railroad, River, Road
Functional Class	4	Interstate, Major Collector, Minor Arterial, Principle Arterial
Design Load	10	HL-93, H-15, H-20, H-10, HS-15, HS-20, HS-20 + mod, ≥ HS-25, Other, Unknown
Bridge Material	8	Concrete, Concrete Continuous, P/S Conc. Continuous, P/S Concrete, Steel, Steel Continuous, Wood or Timber, Other
Bridge Design	13	Arch-Deck, Box Beam or Girders, Channel Beam, Culvert, Girder and Floor-beams, Segmental Box Girder, Slab, Stringer or Multi-Beam, Stringer/Girder, Tee Beam, Truss-Thru, Truss-Deck, Other
Deck Surface	8	Bituminous, Epoxy Overlay, Gravel, Integral Concrete, Latex Concrete or Similar, Low Slump Concrete, Monolithic Concrete, None

3.1 Freeze-Thaw Cycles

Yearly freeze-thaw cycles (FTCs) were estimated by counting each day where the daily minimum and maximum temperatures cross the 32°F ±1°F freezing threshold. FTCs occurring over periods of less than one day were not counted. The weather station data used to estimate FTCs included 64 weather stations and data recorded from 2000 to 2020. Years with less than

300 days of temperature data were excluded from the averages. The daily summaries for the weather stations were sourced from National Oceanic and Atmospheric Administration (NOAA) and the National Centers for Environmental Information (NCEI) archive. This method was inspired by the Great Lakes Integrated Sciences Assessments Center in their models of regional freeze-thaw cycles (GLISA, 2020). The freeze-thaw temperature locations were obtained from the stations shown in Figure 2.

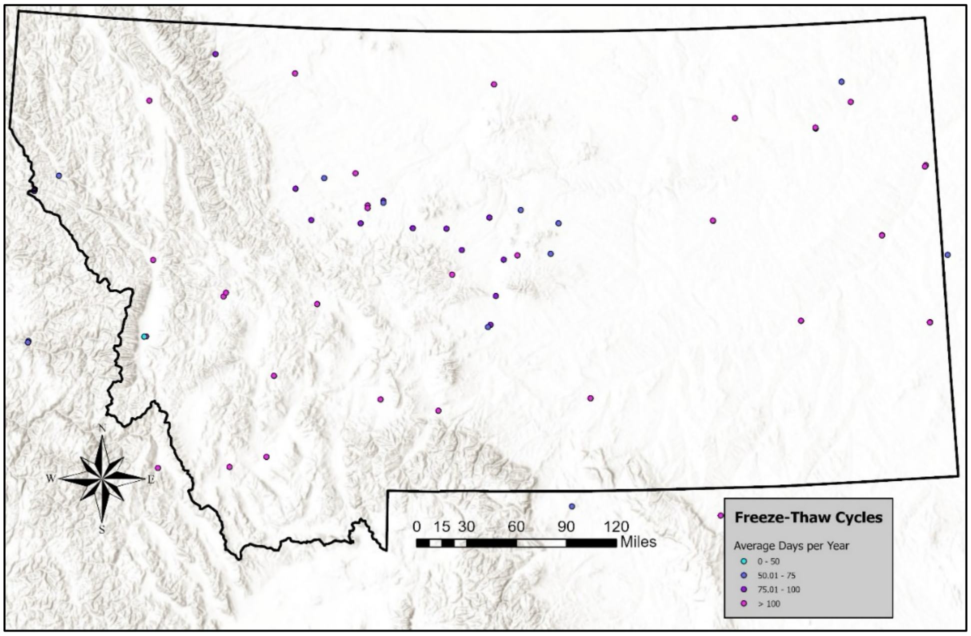

Figure 2: Stations used for the average days per year that experienced a freeze-thaw cycle.

3.2 Precipitation Data

Rain and snowfall data collection sites across Montana were used to determine the influence of precipitation on the deterioration of bridge decks. Latitude and longitude coordinates for each collection site were used to collect data from the station closest to each bridge included in the statistical model.

3.2.1 Rain Data

Yearly rain precipitation estimates were created with data from weather stations in Montana, as well as nearby stations in bordering states and Canada, shown in Figure 3. Daily rain precipitation data from 221 weather stations was obtained from the NCEI online archive which was reduced to 164 by removing 57 stations with insufficient data. Yearly values for precipitation were created by averaging total precipitation daily values for each calendar year between 1935 and 2010.

3.2.2 Snowfall Data

MDT provided a statewide dataset of information for snowfall, which was sourced from NOAA and the NWS. Total daily snowfall data was averaged for 733 weather stations to obtain yearly snowfall averages from 1876 to 2011. The distribution of snowfall recording stations is shown in Figure 4.

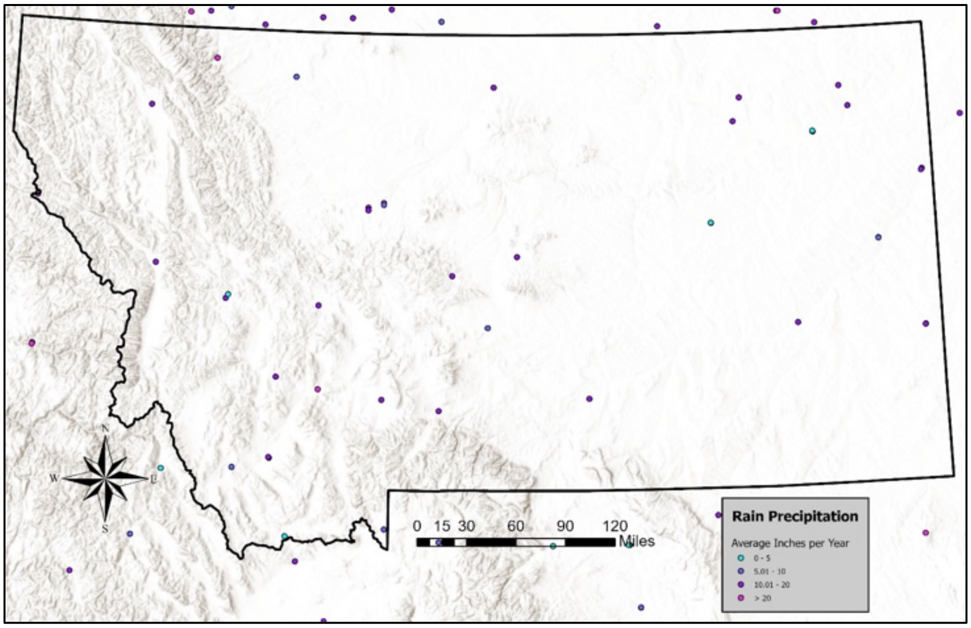

Figure 3: Rainfall data collection stations.

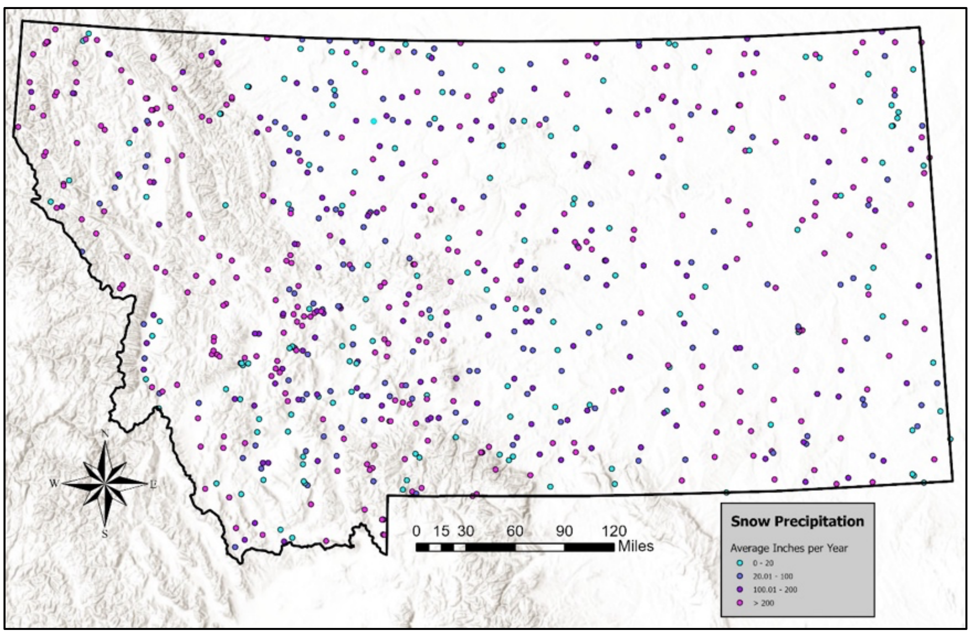

Figure 4: Snowfall data collection stations.

3.3 Deicer Application Rates

The influence of deicer materials on bridge deck deterioration was evaluating using the quantity of deicer applied to bridge decks. Deicer data described by gallons per lane-mile (gal/ln-mi) was obtained from the MDT Maintenance Department. The deicer quantities are divided by the maintenance sections shown in Figure 5. To correlated deicer volumes to individual bridges, the total application quantities for each maintenance section were normalized by the total surface area of the bridge decks in the section. This method assumes consistent application of deicers to all roads and bridges within each maintenance section.

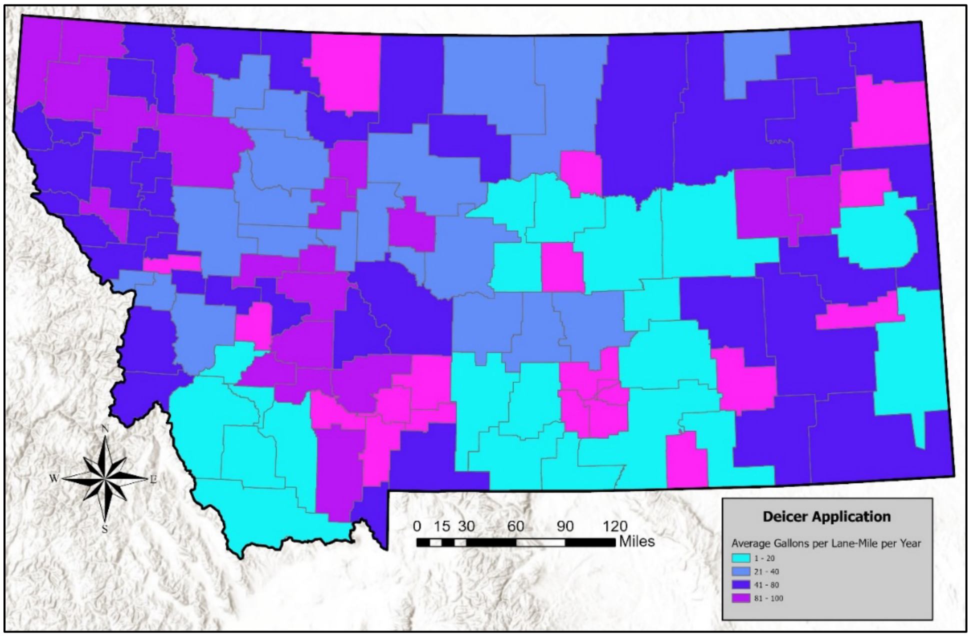

Figure 5: Deicer application rates.

4 Analysis Methods

As described in the Task 2 Report, regression models were used to identify significant factors influencing bridge deterioration by analyzing the relationships between the National Bridge Inventory (NBI) deck ratings and variables. These models quantified the impact of each variable on NBI ratings and estimated the strength and direction of their relationships. The significance of individual variables was determined through statistical tests, such as p-values, to ensure the relationships observed are not due to chance. Data from the 2022 NBI inspection year were used. The same regression models, generalized-linear and random-forest, used in Task 2 were implemented in this Task 3 Report and included the new bridge group and variables.

4.1 Generalized Linear Regression Model

The generalized linear model (GLM) were applied to four bridge groups, described above, including the new deck surface group. All 21 numerical and categorical variables were considered during the first analysis and through iterative refinement, variables with p-values greater than 0.05. The number of remaining variables ranged from five to twelve for the five different bridge groups.

Two performance indicators assessed the GLM accuracy: the adjusted R-squared (R^2), indicating the proportion of variation explained by the model, and the root mean squared error (RMSE), measuring the average difference between predicted and actual values.

4.2 Random Forest

Random Forest (RF) regression models, a machine learning algorithm, was used to analyze the same bridge groups and variables. Each model comprised 500 decision trees, using six random variables per tree. The models identified important variables by the percent increase in mean-squared error (MSE), where larger increases indicated more significant variables.

Two performance indicators were used to assess the RF model accuracy: the mean of squared residuals (MSR), measuring the dispersion of actual and estimated values, and the percentage of variance explained (Pseudo- R^2), useful for comparing competing models.

5 General Condition Rating Analysis

After identifying the significant variables from the regression models, MDT's asset management software, Bridge Management System (BrM), was used to conduct a General Condition Rating analyses (GCR). The GCR uses NBI component-level data to produce Time-in-State reports and Good-Fair-Poor forecasts.

5.1 Time-in-State Report

The first analysis completed through the GCR tool in BrM was the time-in-state report. The analysis considers a user-selected bridge group and calculates the number of years each bridge has remained in the nine NBI component-level condition ratings. The report provides the average years in a condition state with standard deviations based on the total surface area of bridges and by the number of bridges. Based on input from Mayvue Solutions, the average number of years in a condition state plus one standard deviation was selected for the WTI profile used for the Good-Fair-Poor optimization.

5.2 Good-Fair-Poor Forecast

A good-fair-poor forecast within BrM estimates the number of bridges that will be in a condition state in the future, given some level of repair and or maintenance expenditures. "Good" bridges have NBI component-level ratings from 7 to 9, indicating excellent to minor issues. "Fair" bridges include ratings from 5 to 6, with minor to moderate deterioration. "Poor" bridges are rated from 0 to 4 with advanced defects to imminent failure.

The good-fair-poor forecasts in BrM have an option for entering maintenance and/or repair types and frequencies to extend the number of years bridge remain in the 'good' or 'fair' condition. For the GCR analysis described in this Report, no maintenance and/or repair strategies were implemented. Using the WTI profile obtained from the time-in-state report for each bridge group and each condition rating, zero-cost optimizations were run and forecast for 10-, 20-, 30-, 40-, and 50-year intervals. These forecasts were compared with the MDT deck profile to observe differences and compare with the MDT's bridge repair practices and experience. The MDT deck profile was also created with time-in-state reports using different bridge datasets and/or different numbers of standard deviations added to the average times in a condition state.

6 Results

Results of the Generalized Linear regression models, Random Forest regression models and the GCR analysis are presented below.

6.1 Generalized Linear Model

A summary of the significant variables identified using the GLM for each bridge group can be found in Table 3. Cells shaded grey indicate variables that were not included in the model. The adjusted R^2 values for the models ranged from 0.113 for the bridges in the Butte district and 0.356 for bridge decks with an epoxy overlay surface. The RMSE for the GL model ranged from 0.534 for the Glendive district and 1.11 for bridge decks with an epoxy overlay surface.

Table 3: Model performance for each group and significant variables identified in each model.

Bridge Group	Number of Bridges	Adjusted R^2	RMSE	District	County	Age	Max Span Length	Structure Length	Deck Width	Deck Area	Bridge Over	Functional Class	Bridge Skew	AADT	AADTT	Speed	Design Load	Bridge Material	Bridge Design	Deck Surface	Freeze/Thaw	Rain	Snow	Deicer
Statewide	1,686	0.229	0.718	X		X	X		X	X										X			X	X
Billings District	348	0.226	0.628			X	X				X									X				
Butte District	420	0.113	0.669		X	X			X											X			X	
Glendive District	287	0.306	0.534		X	X														X	X			
Great Falls District	282	0.284	1.032		X	X	X					X		X						X				
Missoula District	349	0.294	0.967		X	X	X		X			X				X		X	X	X				
Concrete Main Span	1,366	0.252	0.606	X		X	X	X	X		X	X				X			X	X			X	X
Steel Main Span	311	0.226	1.020	X		X					X	X							X		X			
Interstate Roads	799	0.276	0.670	X		X		X		X	X			X	X		X			X			X	
Major Arterial Roads	360	0.294	0.753	X		X		X			X												X	X
Minor Arterial Roads	290	0.278	0.854	X		X		X		X						X				X	X			
Collector Roads	237	0.249	0.724	X		X		X					X		X					X				
Bituminous Surface	210	0.302	0.867	X		X										X	X				X		X	
Epoxy Overlay Surface	128	0.356	1.114	X		X	X				X		X								X		X	X
Latex Concrete Surface	206	0.321	0.775	X						X				X		X	X						X	
Monolithic Concrete Surface	814	0.231	0.737	X		X				X		X									X		X	X
No Additional Surface	311	0.272	0.748	X		X			X			X												X

The final variables used in each model (p < 0.05) identified with an 'X' in Table 3 were different for each group. The smallest number of significant variables identified was identified in the Billings and Glendive districts with four significant variables. Bridges with a concrete main span superstructure, had the largest number of variables with 12.

The percentage of variables that represented each bridge group, or frequency, can be seen in Figure 6. District or county and age of the bridge were identified as significant variables in over 90% of the models created, and deck surface type were included in over 80% of the bridge models. Snow precipitation was a significant variable in 52% of the bridge groups and functional class was significant in 45% of the bridge groups. All other variables were identified as significant in less than 35% of the bridge models created.

6.2 Random Forest Regression

A summary of the calculated percent increase of the mean-squared error (MSE) for all RF models can be found in Table 4. The most important variables, indicated by large percent MSEs are shaded green. The least important variables are shaded red, and unshaded variables with negative values have a negative effect on the model's performance. The missing values shaded in light grey were not included in the RF model because these groups were also considered one of the variables.

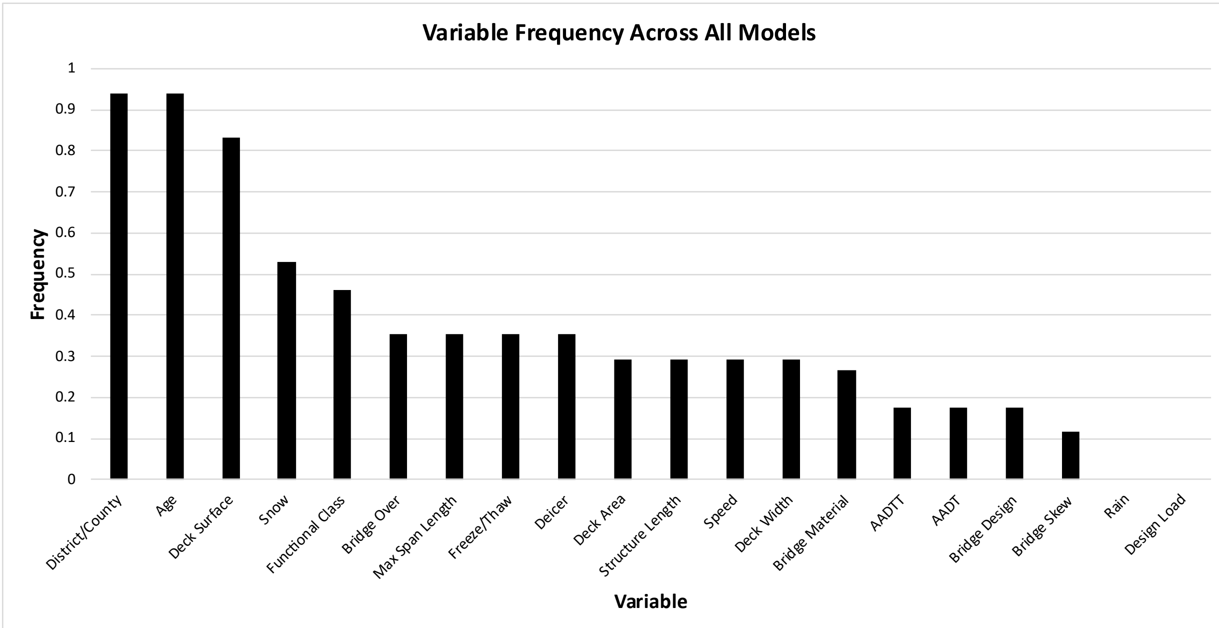

Figure 6: Frequency of variables used in the final models across all the groups.

Table 4: Random forest regression statistical measurements for all the model groups.

Bridge Group	Mean of Squared Residuals	Pseudo-R^2	Percent Increase in MSE																			
			District	Age	Max Span Length	Structure Length	Deck Width	Deck Area	Bridge Over	Functional Class	Bridge Skew	AADT	AADTT	Speed	Design Load	Bridge Material	Bridge Design	Deck Surface	Freeze/Thaw	Rain	Snow	Deicer
Statewide	0.458	0.289	43.7	27.2	20.0	19.0	15.5	18.9	11.3	9.0	6.4	17.4	15.1	8.8	12.1	20.7	7.8	27.8	15.0	15.0	13.4	17.5
Billings District	0.287	0.285		15.3	9.7	14.3	10.5	11.9	16.4	7.3	5.2	8.4	8.5	7.3	8.4	12.6	5.2	8.4	6.8	9.8	7.4	9.5
Butte District	0.359	0.230		17.6	10.1	9.8	20.1	8.4	11.0	7.3	5.6	16.0	11.3	5.8	6.4	10.6	4.4	14.1	6.5	8.5	13.1	9.5
Glendive District	0.258	0.176		15.6	10.6	9.6	10.6	8.7	-0.2	4.0	1.2	5.5	5.5	0.5	-0.2	8.1	4.9	11.4	5.4	5.5	8.7	4.8
Great Falls District	0.656	0.259		12.5	17.6	9.8	7.7	9.9	4.4	8.0	3.9	9.4	9.9	6.9	11.4	10.8	4.5	10.3	2.1	7.8	4.2	7.2
Missoula District	0.635	0.200		13.2	13.5	13.0	5.6	12.4	3.9	12.4	2.7	8.8	8.4	2.2	4.8	9.8	1.4	9.1	5.3	5.8	6.4	5.9
Concrete Main Span	0.414	0.324	47.2	25.9	18.7	15.3	19.0	18.7	13.8	11.9	6.5	19.9	17.2	10.7	11.2	6.0	6.5	29.7	16.8	15.5	16.4	20.3
Steel Main Span	0.620	0.099	12.2	9.2	6.6	6.7	7.0	4.4	3.3	3.0	0.8	4.5	6.0	0.7	4.5	7.6	5.4	9.3	2.4	-0.4	1.8	5.7
Interstate Roads	0.339	0.346	28.0	20.2	18.3	17.3	17.1	17.9	13.6		8.1	21.9	17.7	9.1	4.3	11.6	7.3	24.7	16.2	17.4	14.8	20.8
Major Arterial Roads	0.487	0.258	18.0	14.4	9.7	11.9	7.6	10.8	12.0		-0.9	9.3	4.1	2.9	3.0	8.6	-0.4	5.3	4.3	4.3	8.3	6.0
Minor Arterial Roads	0.676	0.252	12.0	10.8	6.6	11.1	9.9	8.9	3.6		-0.7	7.7	7.0	6.2	5.7	5.4	2.6	4.2	6.4	2.0	4.1	17.0
Collector Roads	0.504	0.139	14.5	6.7	0.7	6.8	5.4	7.6	2.6		1.0	6.8	7.1	-3.9	11.3	2.9	2.3	5.1	4.0	3.7	1.6	5.8
Bituminous Surface	0.494	0.206	14.6	10.2	6.5	5.6	8.3	7.7	2.0	2.2	1.1	0.7	4.6	1.3	3.0	7.3	-0.9		2.4	3.2	5.6	4.1
Epoxy Overlay Surface	0.447	0.134	11.1	11.0	6.0	7.6	7.9	7.6	4.1	2.0	3.8	4.2	2.5	1.8	1.0	5.5	0.4		4.1	3.8	2.5	5.5
Latex Concrete Surface	0.553	0.229	19.1	6.8	10.9	6.8	9.6	7.0	7.0	2.1	1.0	3.7	8.2	3.3	-0.2	7.9	1.7		9.1	2.9	11.5	9.2
Monolithic Concrete Surface	0.445	0.306	32.7	22.8	15.6	18.4	14.9	16.4	8.3	7.5	3.2	13.1	13.1	5.8	5.8	11.9	3.8		14.9	9.0	9.9	17.6
No Additional Surface	0.348	0.253	7.1	25.1	8.6	6.7	8.6	8.9	9.5	4.7	6.2	9.3	7.8	6.5	7.1	4.6	2.5		3.9	7.3	7.4	5.8

To evaluate the RF model prediction accuracy for each bridge group, the average MSE values are shown in Table 5 for statewide, maintenance district, superstructure material, functional class, and deck surface groups. The same color shading shown in Table 4 was used (most significant = green, least significant = red).

6.3 General Condition Rating Analysis

Bridge datasets for the GCR analysis were created within BrM using the same filters as the regression models described above. Only active bridges maintained by MDT with a concrete cast-in-place deck were used for the GCR analysis.

Table 5: Average statistical measurements for the random forest models for each bridge group.

Bridge Group	Mean of Squared Residuals	Pseudo-R^2	Percent Increase in MSE																			
			District	Age	MaxSpan Length	Structure Length	Deck Width	Deck Area	Bridge Over	Functional Class	Bridge Skew	AADT	AADTT	Speed	Design Load	Bridge Material	Bridge Design	Deck Surface	Freeze/Thaw	Rain	Snow	Deicer
Statewide	0.458	0.289	43.7	27.2	20.0	19.0	15.5	18.9	11.3	9.0	6.4	17.4	15.1	8.8	12.1	20.7	7.8	27.8	15.0	15.0	13.4	17.5
Districts	0.439	0.230		14.8	12.3	11.3	10.9	10.2	7.1	7.8	3.7	9.6	8.7	4.6	6.1	10.4	4.1	10.6	5.2	7.5	7.9	7.4
Material	0.517	0.211	29.7	17.6	12.6	11.0	13.0	11.5	8.6	7.4	3.6	12.2	11.6	5.7	7.8	6.8	5.9	19.5	9.6	7.6	9.1	13.0
Functional Class	0.501	0.249	18.1	13.0	8.8	11.8	10.0	11.3	7.9		1.9	11.4	9.0	3.6	6.1	7.1	2.9	9.8	7.7	6.8	7.2	12.4
Deck Surface	0.458	0.225	16.9	15.2	9.5	9.0	9.9	9.5	6.2	3.7	3.0	6.2	7.3	3.7	3.4	7.5	1.5		6.9	5.3	7.4	8.4

6.3.1 *Time-in-State Report*

The BrM time-in-state reports are used to create a profile that is used for the good-fair-poor analysis. The results of the time-in-state reports can be seen in Table 6. For the WTI profile, the average number of years plus one standard deviation for each of the bridge groups shown. Grey shaded values with bold text are values obtained from the time-in-state report. The unshaded '1' values for condition ratings 1-3 were used instead of the zero values generated by the analysis. Unshaded values for condition ratings 8 and 9 also produced zero values from the time-in-state report and were replaced with the values for the state-wide bridge group. Also shown in Table 6 are the median number of years in each condition state using the MDT Deck Profile.

Table 6: Time-in-state GCR values for each of the bridge groups.

Bridge Group	Number of Bridges	Median Years in NBI Rating								
		9	8	7	6	5	4	3	2	1
MDT Deck Profile	1,890	10	4	28	20	22	11	10	10	10
Statewide	1,890	**4**	**4**	**33**	**21**	**16**	**16**	**10**	1	1
Billings District	400	4	**3**	**37**	**24**	**23**	**13**	1	1	1
Butte District	469	4	4	**30**	**21**	**15**	**3**	**1**	1	1
Glendive District	328	4	4	**28**	**21**	**20**	**2**	1	1	1
Great Falls District	323	**4**	**5**	**33**	**27**	**21**	**20**	1	1	1
Missoula District	370	4	4	**30**	**18**	**10**	**16**	**10**	1	1
Concrete Main Span	1,517	**4**	**5**	**33**	**21**	**16**	**12**	**10**	1	1
Steel Main Span	363	4	**4**	**28**	**25**	**17**	**21**	**1**	1	1
Interstate Roads	813	4	**4**	**29**	**21**	**14**	**4**	1	1	1
Major Arterial Roads	365	4	**3**	**32**	**20**	**13**	**11**	1	1	1
Minor Arterial Roads	297	**4**	**6**	**31**	**25**	**17**	**16**	**10**	1	1
Collector Roads	273	4	**4**	**35**	**22**	**24**	**3**	**1**	1	1
Bituminous Surface	286	4	**6**	**36**	**21**	**17**	**25**	**1**	1	1
Epoxy Overlay Surface	144	4	**3**	**28**	**22**	**10**	**10**	1	1	1
Latex Concrete Surface	223	4	**3**	**27**	**20**	**12**	**6**	1	1	1
Monolithic Concrete Surface	875	**4**	**5**	**34**	**22**	**19**	**15**	1	1	1
No Additional Surface	345	4	**1**	**28**	**23**	**16**	**3**	1	1	1

6.3.2 *Good-Fair-Poor Analysis*

Each of the bridge groups were analyzed using a no-cost Good/Poor optimization within BrM for the WTI and MDT GCR profiles. The results of the statewide analysis can be seen in Figure 7. The downward trends of the Good (green) and Fair (yellow) lines represents fewer bridges in these condition states over time because maintenance activity has been excluded. Conversely, the upward trend of the Poor (red) line increases because of the bridges moving into this condition state in the absence of maintenance activity (zero-cost). Similar plots for the bridge groups shown in Table 6 can be found in Appendix 1: Good-Fair-Poor Plots.

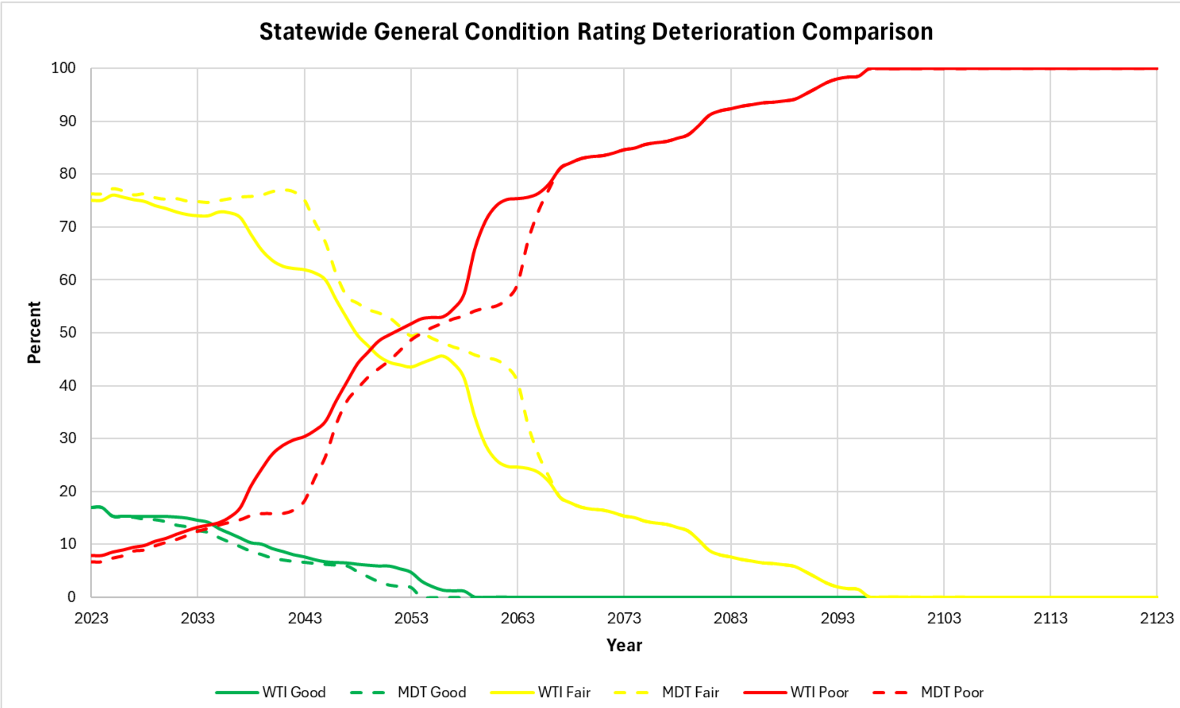

Figure 7: Good-fair-poor analysis comparison between default MDT Deck Profile and established WTI GCR deterioration values.

One way to quantify the trends shown in the good-fair-poor analysis is to consider only the percentage and number of bridges estimated to be in poor condition over 10-year time periods as shown in Table 7 and Table 8 for both the WTI and MDT profiles. The number of bridges in each group (Table 8) were added together to estimate the number of bridges in the poor condition over a 50-year period using a no-cost optimization. A plot of the WTI and MDT estimates is shown in Figure 8.

Table 7: Percentage of bridges in poor condition for bridge groups considered.

Bridge Group	Percent of Bridges in Poor Condition									
	10 years		20 years		30 years		40 years		50 years	
	WTI	MDT	WTI	MDT	WTI	MDT	WTI	MDT	WTI	MDT
Statewide	13.3	12.5	30.4	18.1	51.7	48.6	75.4	59.2	84.6	84.6
Billings District	12	12	13.5	14.1	45.8	48.1	55.8	58.1	79.9	82.3
Butte District	5.5	4.8	24	7.7	50.7	43.4	80.5	58.3	91.3	90.6
Glendive District	12.4	11.5	21.3	15.6	48	47	76.2	60.8	93.2	93
Great Falls District	9.3	9.3	20.5	13.7	37.6	44.1	51.3	51.2	69.7	72.4
Missoula District	36.6	21.8	50	34.4	74	57.5	79.3	64	93	85.4
Concrete Main Span	7.8	6.5	22.5	10.1	44	41.3	71	51.8	82.7	82.7
Steel Main Span	21.7	21.5	39.5	30.3	59.6	59.6	70.3	70.3	87.4	87.4
Interstate Roads	8.4	7.7	26	13.9	53.6	48.4	77.3	62.6	89	87.2
Major Arterial Roads	17	13	38.5	19.6	50.6	47.3	73.2	53.1	83.4	81.4
Minor Arterial Roads	22.2	21.7	34.3	28.5	49.7	49.7	59.3	59.3	82.2	83.8
Collector Roads	14.1	14.1	16	16	47.7	48.6	58.1	55.6	81.5	85.4
Bituminous Surface	16.6	16.6	26.4	19.9	46.9	45.8	64.7	56.6	73.9	74.7
Epoxy Overlay Surface	23.9	14.4	35.7	25.4	57.7	50.9	70.2	61.6	84.9	81.2
Latex Concrete Surface	17.3	11.8	32.7	21.8	56.5	52.1	79.4	60.7	93.4	87.8
Monolithic Concrete Surface	13.1	12.5	26.9	16.5	48.6	48.1	67.3	58.2	83.1	85.7
No Additional Surface	7	6.6	25	10	46.2	41.6	75.8	56.1	84.5	84.3

Table 8: Number of bridges estimated to be poor condition state-wide using no-cost analysis.

Bridge Group	Number of Bridges in Poor Condition									
	10 years		20 years		30 years		40 years		50 years	
	WTI	MDT	WTI	MDT	WTI	MDT	WTI	MDT	WTI	MDT
Statewide	251	236	575	342	977	919	1425	1119	1599	1599
Billings District	48	48	54	56	183	192	223	232	320	329
Butte District	26	23	113	36	238	204	378	273	428	425
Glendive District	41	38	70	51	157	154	250	199	306	305
Great Falls District	30	30	66	44	121	142	166	165	225	234
Missoula District	135	81	185	127	274	213	293	237	344	316
Concrete Main Span	118	99	341	153	667	627	1077	786	1255	1255
Steel Main Span	79	78	143	110	216	216	255	255	317	317
Interstate Roads	68	63	211	113	436	393	628	509	724	709
Major Arterial Roads	62	47	141	72	185	173	267	194	304	297
Minor Arterial Roads	66	64	102	85	148	148	176	176	244	249
Collector Roads	38	38	44	44	130	133	159	152	222	233
Bituminous Surface	47	47	76	57	134	131	185	162	211	214
Epoxy Overlay Surface	34	21	51	37	83	73	101	89	122	117
Latex Concrete Surface	39	26	73	49	126	116	177	135	208	196
Monolithic Concrete Surface	115	109	235	144	425	421	589	509	727	750
No Additional Surface	24	23	86	35	159	144	262	194	292	291

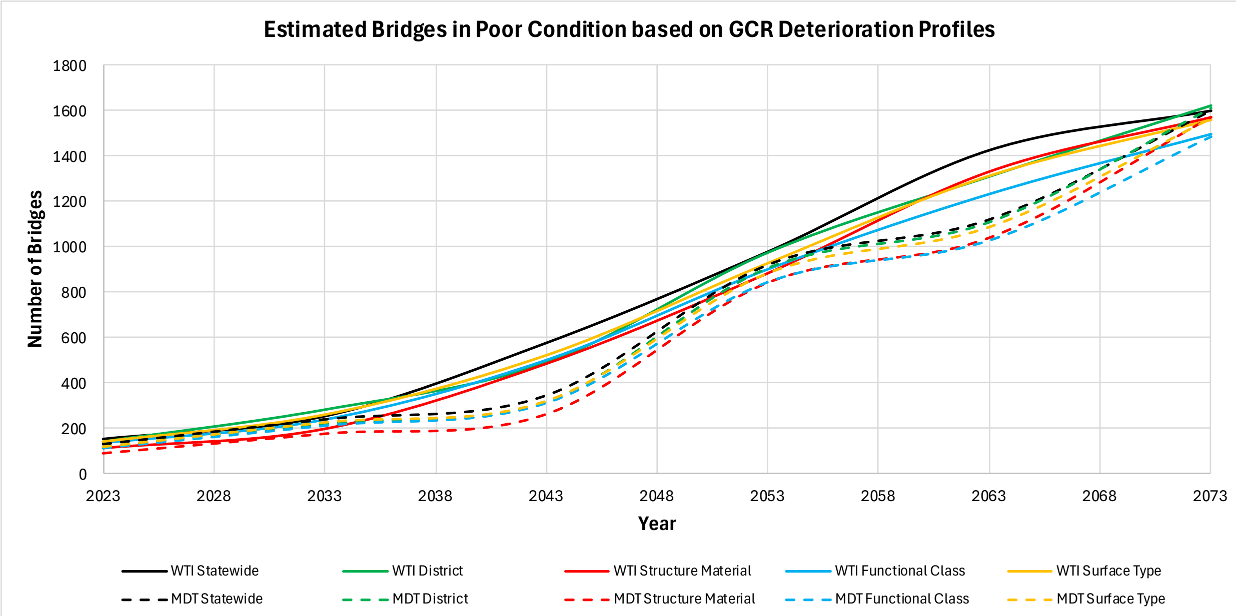

Figure 8: Estimated number of bridges in poor condition based on WTI and MDT GCR deterioration profiles based on no-cost optimizations.

7 Summary and Discussion

The GLM and RF regression models were used to determine which variables had the highest influence on the NBI concrete deck ratings. There was a large variation in the statistical performance indicators of the two model types which are shown in Table 9. A comparison of the performance indicators for each model type, observations related to the significant variables, and results of the GCR analysis are discussed below.

Table 9: Comparison of statistical results for generalized linear and random forest regression models for each bridge group.

Bridge Group	GLM		RF	
	Adjusted-R^2	RMSE	Pseudo-R^2	Mean of Squared Residuals
Statewide	0.229	0.718	0.289	0.458
Districts	0.244	0.766	0.230	0.439
Material	0.239	0.813	0.211	0.517
Functional Class	0.274	0.750	0.249	0.501
Deck Surface	0.296	0.848	0.225	0.458

7.1 Generalized Linear Regression Model

The calculated adjusted-R^2 values for the GLM are low (<0.5), which was expected due to the large number and overlapping influence that different variables have on bridge deterioration. The bridge group with least accurate prediction capability based on the RSME performance indicator was the deck surface group with an average RMSE of 0.848 (Table 9). These values show, on average, the deck surface group was the least accurate predicter of bridge deck NBI ratings.

Based on the results from the GLMs the most accurate model to predict deck NBI ratings is the statewide bridge group, but this model also has the lowest adjusted-R^2 value (Table 9). This means that overall, the variables do a poor job at explaining the variance in the model. This highlights the importance of breaking the bridges into more specific groups. The highest adjusted-R^2 value, and the models that is best fit from this data was the deck surface bridge groups (adjusted-R^2 = 0.296). Even though it is the best fit model for the bridge groups considered, the variables only explain 30% of the variation in NBI deck ratings that can be predicted from the selected variables.

7.2 Random Forest Regression Models

There were similar differences between the performance measurements for the RF regression models. Based on the calculated averages (Table 9), the results did not reveal a consistent improved prediction of NBI ratings in the model groups using the pseudo-R^2 and the Mean of Squared Residuals (MSR) performance indicators.

The bridge group with least accurate prediction capability based on the MSR value from the RF regression models was the superstructure material group (MSR = 0.517). However, all the bridge groups had similar values, with MSR ranging from 0.439-0.517. These models are generally predicting at the same accuracy, on average, to the GLM analysis. The percent of the variance of the NBI deck ratings that can be explained by the selected variables are also similar to the GLM analysis. The pseudo-R2 values ranged from 0.211-0.289 (Table 9), with the largest value in the statewide bridge group. The RF analysis suggests that the bridge group best described by the selected variables is the statewide bridge grouping.

In general, considering the number of iterations and their adaptability to multiple datasets, the RF regression models may be a better representation of the performance of NBI deck rating predictor models and hold a higher weight to variable selection. This observation is highlighted in the statewide bridge group analysis where the largest number of bridges produced the highest described variance compared to the other smaller bridge groups using the same variables in the model.

7.3 Variables

Including the additional variables (e.g., snow, rain, freeze-thaw, and deicer), and removing non-significant variables in the analysis, did not significantly change the performance of the models when compared to the Task 2 analysis. It also did not change the significance of the previously identified variables. Rather it generally kept the variables in the same order as Task 2, with the addition of the new variables slotted into position. The ranking of the significance of the variables from the GLM and RF models can be seen in Table 10.

Table 10: Significant variable ranking for generalized linear and random forest models.

Model	District/County	Age	Deck Surface	Max Span Length	Bridge Over	Snow	Deck Area	Structure Length	Deicer	Deck Width	Freeze/Thaw	Functional Class	Bridge Material	AADT	AADTT	Speed	Rain	Bridge Design	Design Load	Bridge Skew
GLM	1	2	3	7	6	4	10	11	9	13	8	5	14	16	15	12	19	17	20	18
RF	1	2	3	4	6	12	6	5	8	7	13	17	10	9	11	18	14	19	16	20
Average Ranking	1	2	3	5.5	6	8	8	8	8.5	10	10.5	11	12	12.5	13	15	16.5	18	18	19

The top three identified significant variables are district/county, age of the bridge, and surface type, for both GLM and RF models. After the top three, the two model types start to vary in their selection of significant variables. On average, max span length and the feature the bridge crosses are the two most significant variables. Snow is identified as the 6th most significant variable, on average, but it was ranked 4th in the GLM and 12th in the RF regression. Deck area, structure length, deicer application, and deck width are the 7th through 10th most significant variables based on the two model types Table 10.

Freeze-thaw cycles were ranked as the 11th most significant variable, on average, and rain precipitation was ranked 17th. Based on the results of the analysis, the location of the bridge (e.g., district or county), bridge properties (e.g., age and dimensions), and winter conditions (e.g., snow precipitation, deicer application, and freeze-thaw cycles) are the most significant factors identified for predicting NBI deck rating deterioration.

7.4 General Condition Rating Analysis

A procedure was established using BrM's general condition rating (GCR) analysis to estimate the number of bridges that are in good, fair, and poor condition over selected time periods. The analysis performed in this research used a zero-cost optimization and 10-year time intervals up to 50-years.

The zero-cost optimizations were completed using two different deterioration profiles. The WTI profile completed time-in-state reports for each of the bridge groups shown in Table 3 and used the average transition time for each condition state plus one standard deviation. The MDT deck profile shown in Table 6 was created using different bridge groups and different transition time estimates and were guided by experience from MDT and Mayvue.

When comparing the number of bridges in poor condition (Figure 8) for the MDT and WTI profiles, it is observed that the number of bridges in poor condition are generally the same at the start of the analysis, and after 50 years. The difference between the two profiles occurs in the time period of 20 and 40 years, where the MDT profile predicts fewer bridges moving to a poor condition. These flat regions or regions where fewer bridges are transitioning to a poor condition likely reflect maintenance activity that was generally accounted for through experienced selection of the transition times shown in Table 6

8 References

[1] Iranitalab, A. and Khattak, A. (2017) ‘Comparison of four statistical and machine learning methods for crash severity prediction’, *Accident Analysis & Prevention*, 108, pp. 27–36. Available at: https://doi.org/10.1016/j.aap.2017.08.008.

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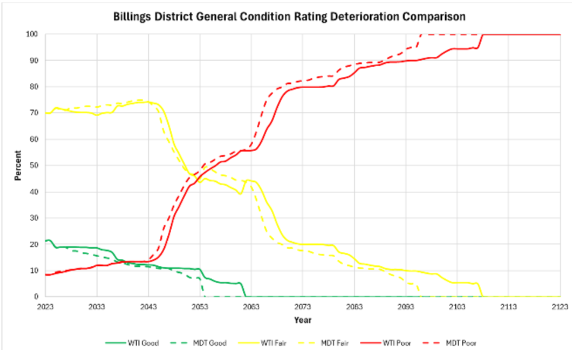
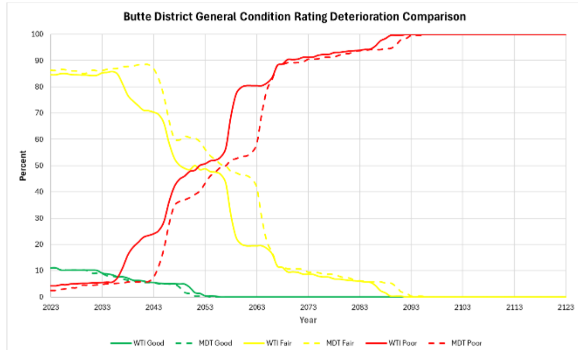
[3] R Core Team (2023) ‘R: A Language and Environment for Statistical Computing’. Vienna, Austria: R Foundation for Statistical Computing. Available at: http://www.R-project.org.

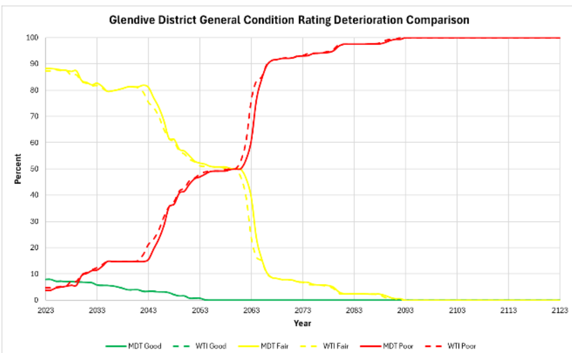
[4] Schlögl, M. *et al.* (2019) ‘A comparison of statistical learning methods for deriving determining factors of accident occurrence from an imbalanced high resolution dataset’, *Accident Analysis & Prevention*, 127, pp. 134–149. Available at: https://doi.org/10.1016/j.aap.2019.02.008.

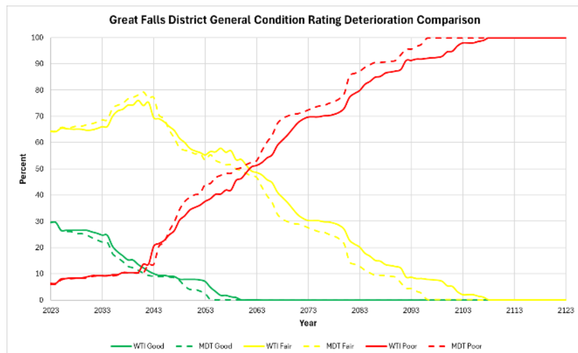
9 Appendix 1: Good-Fair-Poor Plots

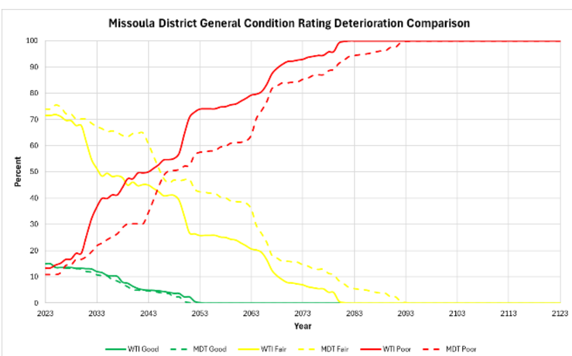
9.1 District Plots



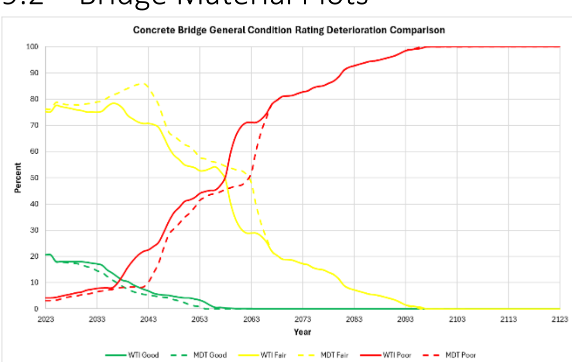


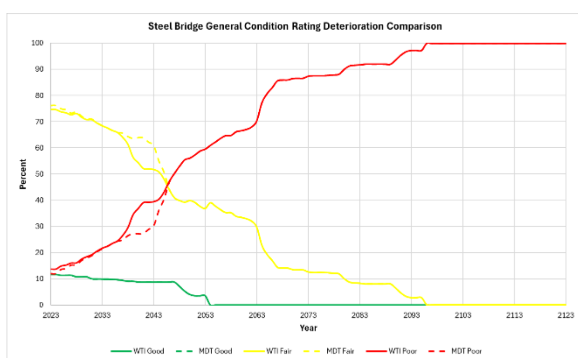




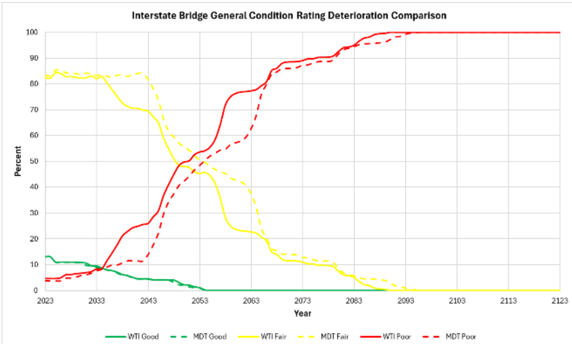


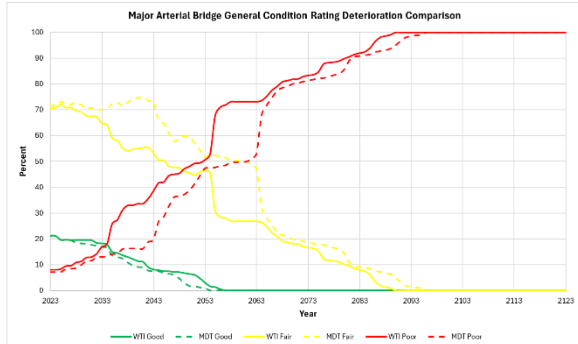
9.2 Bridge Material Plots

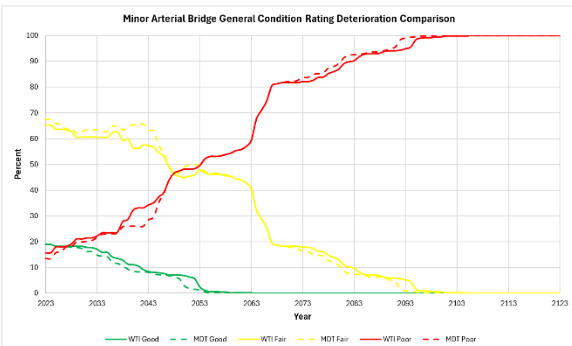


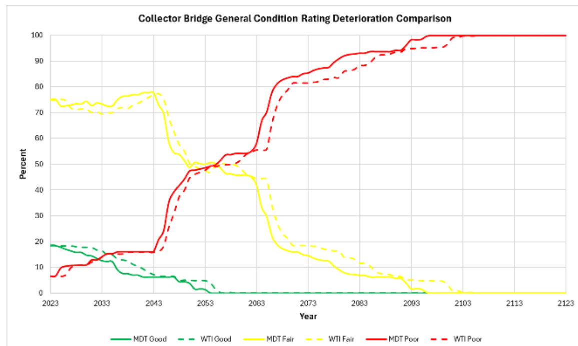


9.3 Functional Class Plots

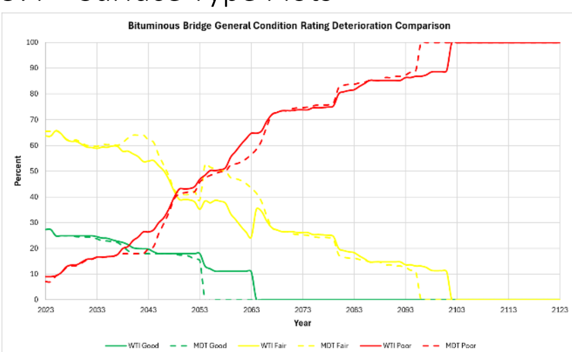


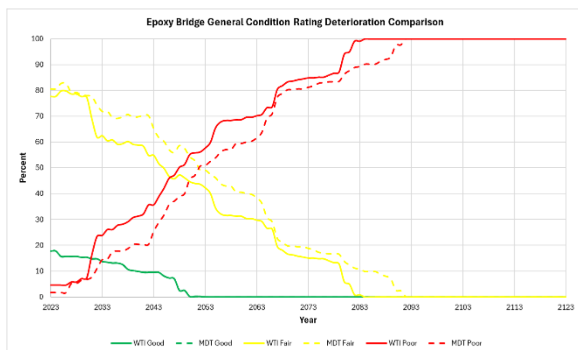


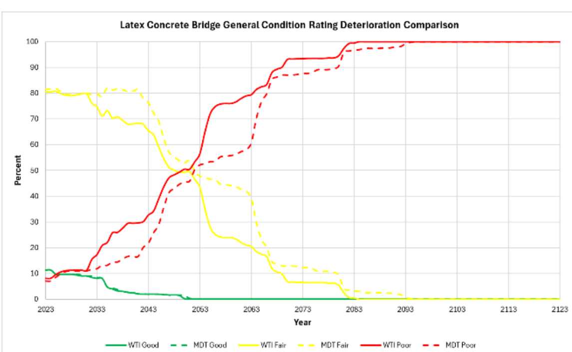


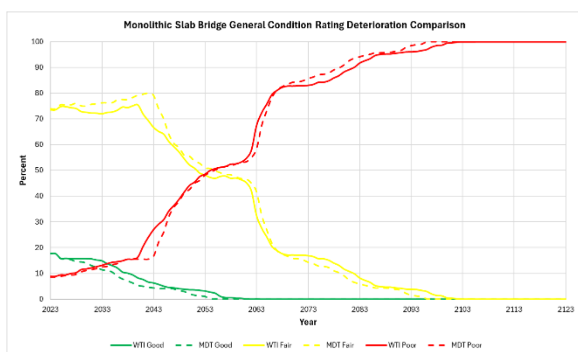


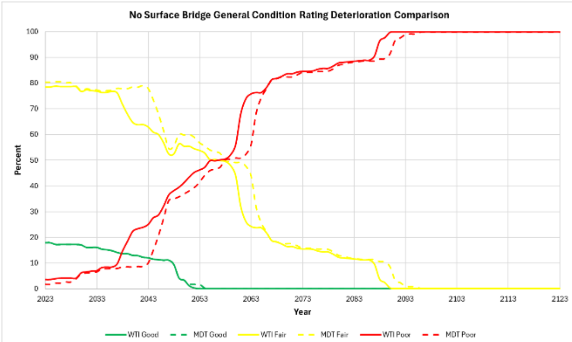
9.4 Surface Type Plots










No Surface Bridge General Condition Rating Deterioration Comparison
Percent
100
90
80
70
60
50
40
30
20
10
0
2023
2033
2043
2053
2063
2073
2083
2093
2103
2113
2123
Year
WTI Good
MDT Good
WTI Fair
MDT Fair
WTI Poor
MDT Poor