The database of the Icelandic bridge management system

Unnið fyrir Rannsóknarsjóð Vegagerðarinnar

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Abstract

A fundamental requirement for road safety is bridge maintenance. In order to achieve safety, regular and efficient inspections must be implemented. The purpose of this paper is to access the conditions of the Icelandic bridges, in order to plan maintenance or demolition. This paper defines the relationship between the last inspection grade condition and the age of the bride, by implementing a regression analysis on the available data. In the case study, 1146 bridges have been implemented in a linear and non-linear regression analysis were the overall grade has been combined with other variables. The results show that age is the variable most affecting the overall grade, and between the bridge components, the foundation is the one most affecting the grade.

Keywords: bridge, inspection, grade system, maintenance, management, bridge database

Acknowledgment

The authors would like to express their sincere appreciation to those who made this research possible, who supported them and contributed to the bag of knowledge within this paper. The authors understand a research of this kind not only improves personal skills and personal knowledge; but, as importantly, it is a great way to meet the leading figures within the civil engineering field in Iceland.

First and foremost, the authors wish to place on records their supervisor Dr. Haraldur Sigþórsson for providing them with the opportunity of studying an important and useful topic for the Icelandic society; at the same time, Haraldur was giving the authors the chance to meet dedicated engineers that work in the field. The authors appreciate his contributions of time and ideas to make their work productive and stimulating. With his valuable suggestions, comments, and guidance Haraldur encouraged both authors to learn more day by day. In addition, Haraldur was a great source of information not only for the Icelandic culture but also for the German and the Kiwi one (New Zealand); with his stories, comments and curious facts, Haraldur made every meeting an unforgettable experience.

The authors are extremely grateful to Prof. Eyþór Rafn Þórhallsson, associate professor in the civil engineer department at Reykjavik University, who is constantly helping them during their career at the Master studies and who gave them the opportunity to challenge themselves with the current research.

Sincere gratitude is reserved for engineer Aron Bjarnason, the engineer behind the Icelandic bridge management (IBM) database. Without his work, this research wouldn't be possible. The authors really appreciate his willingness to help them understand the IBM system and the time that he dedicated them. Along with engineer Aron, the authors would like to thank the Icelandic institution Vegagerðin, a welcoming place and the institution that made this research possible.

The authors are also indebted to MSc Guðmundur Úlfar Gíslason, not only because the current research is based on part of his previous work at Reykjavik University, this last been his Master thesis in 2017. But also, because without his permission to use part of the material that he previously researched, the authors wouldn't have been able to finish their research in such a short amount of time.

The authors would also like to take this opportunity to thank engineer Guðmundur Valur Guðmundsson, Head of Road and Bridge design, Icelandic Road and Coastal Administration (IRCA), who gave us interesting material to look up about quality specifications for roadway bridges, standardised at a European level (Cost Action TU1406), and who reviewed our reference list.

Preface

Every country in the world has bridges as a fundamental part of the interconnections between regions, municipalities, cities, houses, etc. A bridge is "a structure that is built over a river, road, or railway to allow people and vehicles to cross from one side to the other", as it is stated in the Cambridge dictionary. What is not stated in the definition, but of obvious importance, is that a bridge must be a safe structure, so that the people or vehicles can cross it within an acceptable level of risk.

As soon as a bridge is built, its conditions start to get worst [1]. The environment plays a decisive role in the degradation of the materials composing the infrastructure; exposure to water and moisture, melt-freeze cycle, solar exposure, chemicals (i.e. salt), are just a few of the degradation factors, but all well clear in the reader's mind [2]. Iceland has an aggressive environment. To keep Icelandic bridges within an acceptable level of risk, a bridge management system had been implemented as well as periodic *in situ* inspections [3].

The authors of this paper focus on the bridge management system (BMS). "Effective management of a bridge requires decision-makers to design and execute programs that maintain or extend bridge life at low cost", thus it "is a comprehensive decision-making process that entails consideration of the cost and effectiveness of follow-up actions (repair/rehabilitation) corresponding to accurate condition ratings" [1]. The Icelandic rating condition and BMS are explained in the current research through the words of Guðmundur Úlfar Gíslason.

Previous research in the field of bridge management systems has been conducted by Guðmundur Úlfar Gíslason, *"Þróun einkunna við ástandsskoðun steinsteyptra brúa á íslenska vegakerfinu",* 2017. The authors of this paper have found the aforementioned research of absolute importance; not only because it explains how the bridge management system works in Iceland compared to other systems in others countries, but also because it reveals some aspects of the Icelandic maintenance system that are the foundation of the current research.

In the following chapter, with the authorisation of Guðmundur Úlfar Gíslason, the authors are going to reuse some of the definitions, pictures, and graphs, in order to introduce the topic and in order to set the base for this paper research. In addition, the authors discuss some different points of view, specifically while comparing the grading method used by Guðmundur Úlfar in his Master thesis and the method used in the current research.

Introduction

Bridge Management Systems are used to oversee design, construction, operation, condition of inspections, and bridge maintenance. Because funds are often scarce, authorities in many countries face numerous challenges, such as to perform maintenance on road-related structures. By having a bridge management system, you can better define the factors that need to be considered when assessing the need for maintenance [4].

FIGURE 1-1 - MEASURING OF STEEL STRUCTURE THICKNESS [4].

Bridge inspections are one aspect of BMS where the condition of bridges is assessed based on certain factors. Among the inspecting techniques, usually visual assessment is the one more often performed. Certain elements can also be tested by other methods, such as calculating models, in order to estimate load capacity or a variety of different measurements (cranking, strength testing of concrete samples) and various other studies.

In Figure 1-1, e.g. it can be seen the measuring method of the thickness of the rust protection on steel structures. The factors considered are thus given a predefined rating according to the situation, called grades in this paper. Data is then collected, over a specific period, in a standardised way that is then used to assess the condition of the bridge in question. Thus, the need and the timing for maintenance of the structures can be assessed. In addition, the safety of the structure is better ensured, which benefits everyone [5].

In the Icelandic highway system, there are up to 1146 bridges with a total length of over 31,000 meters. All the bridges are supervised by the Road Administration (Vegagerðin), and they are inspected with a nationally standardised bridge inspection system. However, some bridges are supervised by local authorities, this fact leading to some inconsistencies because of different supervision methodology. The system used by the Road Administration to manage the bridge inspections is run in "Microsoft Access", which is in the Office software package. "Microsoft Access" is a database system used for recording, editing, publishing, and managing data. The bridge inspection system was originally created by the Road Administration's employees in 1995. The main purpose of the system is that people can have an overview of the development of the state of the bridge. This way, preventive maintenance, and costly repairs can be planned with respect to the available capital at any given time [6].

The bridges are inspected every four years by the Road Administration inspectors. The bridge is divided into five sections. Under each building section, there are many different damage categories and then there are rating categories for each damage category (the grades). A rating from 0 to 5 is given, where the rating 0 corresponds to a new building component and rating 5 means the most damage and immediate maintenance. For certain concrete structures, a grade of 8 is also given. This only applies if the cast iron has become heavily rusted and therefore requires special inspection. For each rating, the extent of the damage is then recorded. Figures 1-2 show how the classification is recorded in the bridge inspection system [3].

FIGURE 1-2 - Building components in the Road Administration's bridge inspection system (Icelandic language)

As shown in Figure 1-2, each bridge is divided into five building blocks, each with its own key number. Under each building component, there are many different unit parts that also have their own key numbers. The corresponding components are, in English:

- 100: Foundation (pile footing, land piles, intermediate columns, abutment, pier)
- 200: Structure (cap, seats, and beams, girder)
- 300: Deck (deck, approach slab, kerb)
- 500: Soil section (wingwall, slope protection, breast wall, approach embankment)
- 600: Accessories (handrails, barrier rail, bearings, pipes, drains, expansion joint, parapet)

Figure 1-3 and figure 1-4 show the classic bridge terminology related to the bridge parts.

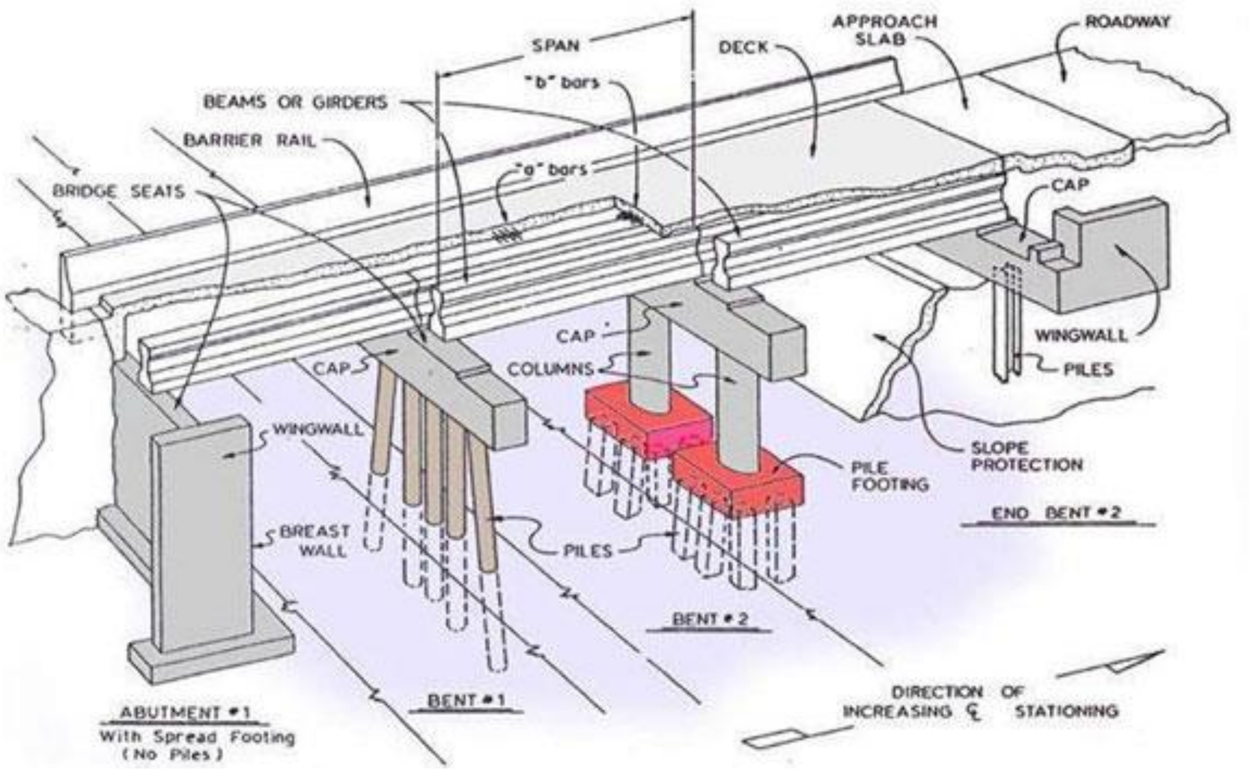

FIGURE 1-3 – Bridge terminology [7] from Sketchup3DConstruction.com

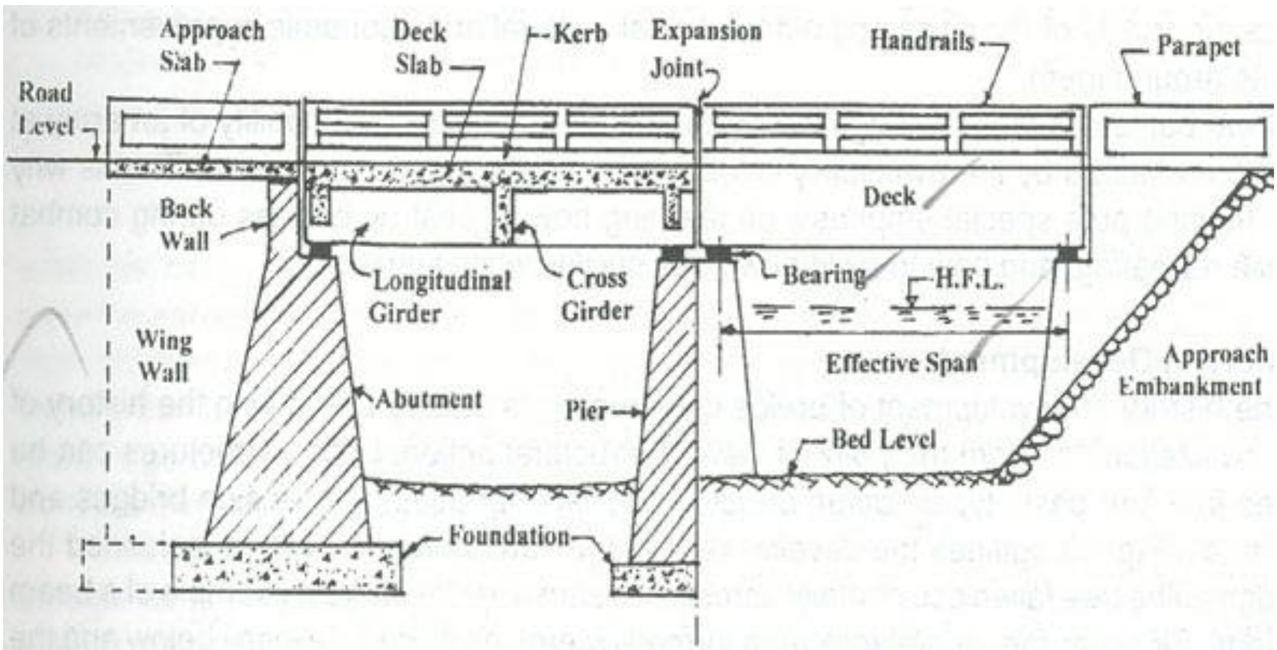

FIGURE 1-4 – Bridge terminology [7] from Sketchup3DConstruction.com

The system is structured in such a way that it is easy to edit and add categories that need to be viewed, e.g. damage categories, unit categories, etc. It is also easy to change the weight of grades on individual inspection items. It is flexible and relatively easy to use. It is easy to query the data that needs to be viewed, as the data is broken down into tables. Therefore, it is easy to print charts, graphs, etc. [3]

This research aims to discover how much the overall grade of each bridge in Iceland is affected by the age; which one of the bridge components is mostly affecting the overall grade; how much is the vehicles traffic volume over the bridges affecting the overall grade; how much the length of the bridges is affecting the overall grade.

Examination of the bridge component

The components and the grading system

The main emphasis of the research carried out by Guðmundur Úlfar was to examine the development of the grading method of concrete bridges in Iceland. All bridges in Iceland are divided into regions, i.e. north, south, west, and east. Figure 2-1 shows the division of areas. Grades are compiled from all the opinions on different inspections that have been carried out since 1995 when the Road Administration's bridge inspection system was implemented. However, the most important is the latest state inspection of each bridge and the grades that appear in those inspections [3].

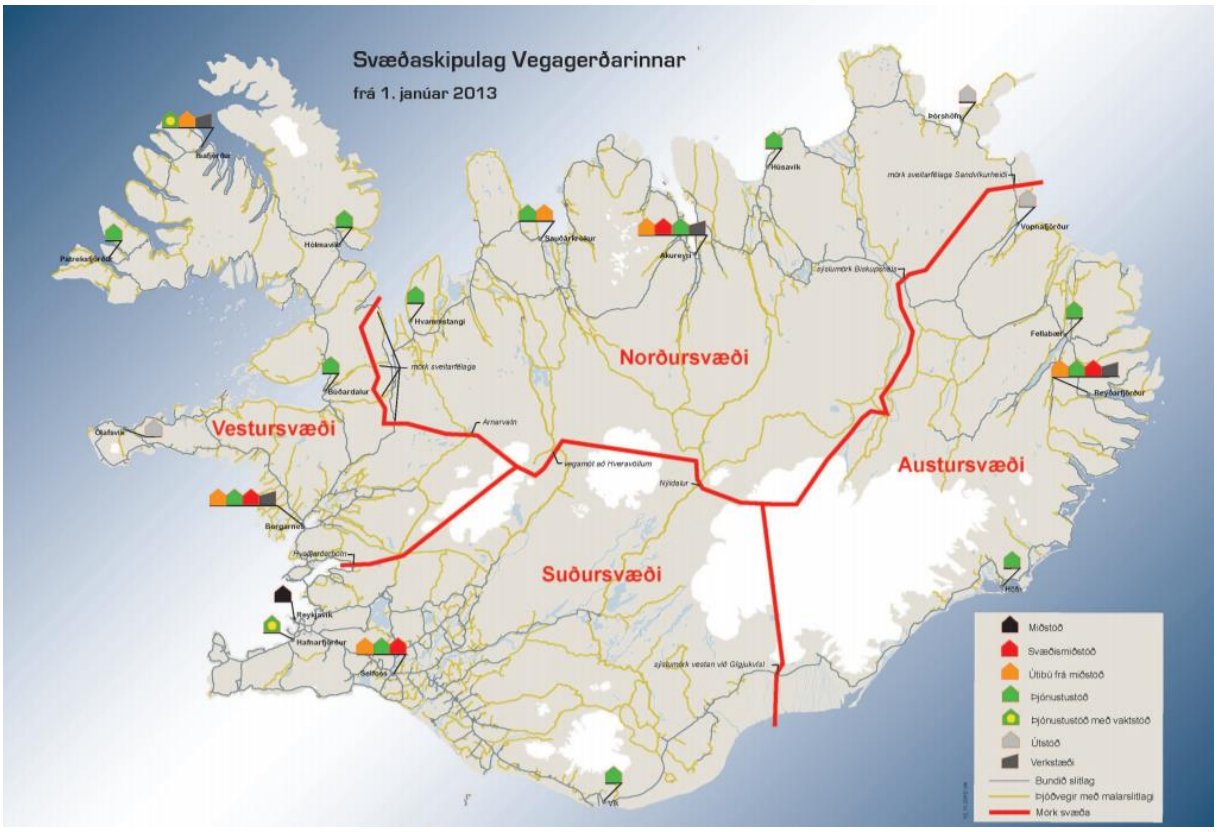

FIGURE 2-1 - REGIONAL PLANNING OF THE ROAD ADMINISTRATION [8].

In order to better understand how the state inspection of the bridge structures is carried out, examples are shown here with pictures of the bridge over Fljótsvegur at Akurey in Rangárþing eystra. Constructed in 1968, the bridge is 20 meters long, with a single lane and is designed for a 34-tonne truckload [10]. The bridge was last inspected in 2015. As previously stated, it is primarily a visual inspection where damage is assessed. The building parts that are inspected are marked in the pictures and the grades are summarized in Table 3-1 below in the section. These grades are then recorded in the Road Administration's inspection system, which then forms the database based on the maintenance and operation of the structures [3].

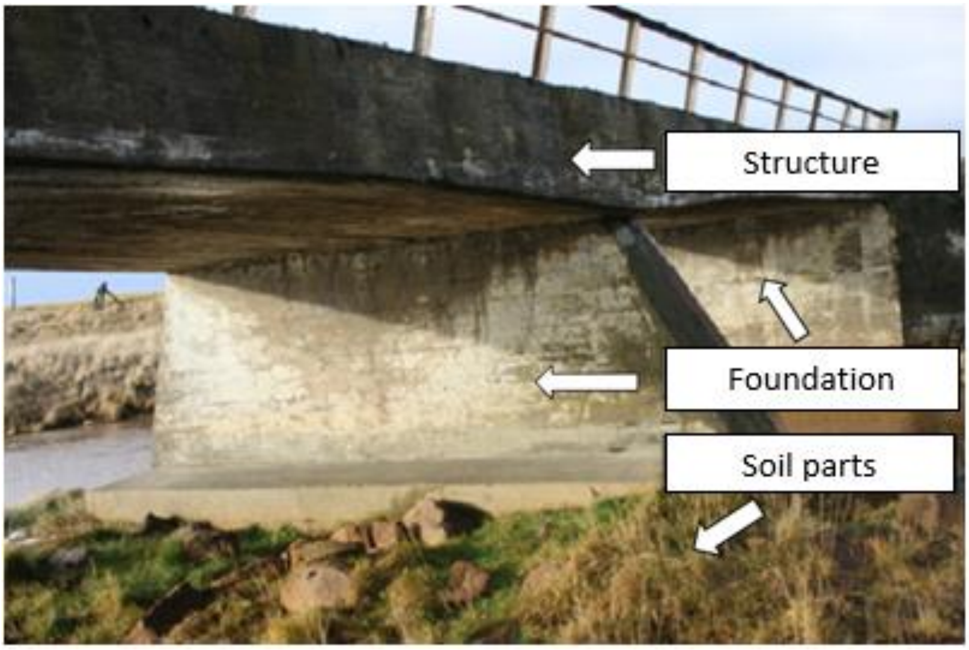

FIGURE 2-2 – CONSTRUCTION PARTS EXAMINED [10].

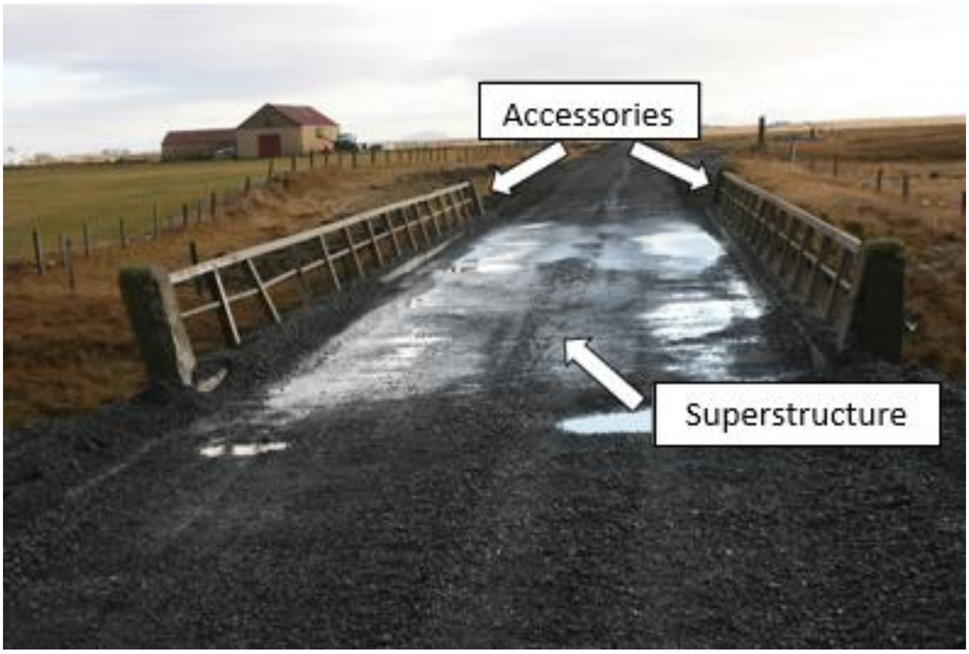

FIGURE 2-3 – CONSTRUCTION PARTS EXAMINED [10].

The table below (table 2-1) shows the grades that each bridge component received during several inspections [3]. Guðmundur Úlfar reported, in table 2-1, the sum of the grades for each component and at the end, the sum of all grades; so that for each inspection a final sum of all bridge components made the bridge grade. This way the bridge grade can reach really high numbers, quite far from the mentioned grade rating system (from 0 to 5). Figure 2-4 shows how the development of the state rating on the bridge over Fljótsvegur, over the period covered by the inspections. Grades are reduced from the first inspection carried out in 1997 and for inspection in 2011 [3]. This can be attributed to the fact that corrections have been made to the parts that have been found deteriorated at each inspection [11]. The rating rises quite much in 2015; that can largely be attributed to the fact that concrete in the foundations has begun to peel a lot and that cracks are starting to form. In accessories, there is also an increase that can be attributed to the handrail condition; it has become much damaged [3].

Skoðun [ár]	Burðarvirki einkunn	Undirstöður einkunn	Yfirbygging einkunnn	Aukahlutir einkunn	Jarðvegshlutar einkunn	Samtals einkunn
1997	2	21	1	4	0	28
2002	5	14	1	1	1	22
2003	2	10	3	1	2	18
2007	3	9	4	1	0	17
2011	3	5	1	1	0	10
2015	2	12	3	4	1	22

TABLE 2-1 - GRADES ON BUILDING SECTIONS FOR EACH INSPECTION, FLJÓTSVEGUR BY AKUREY IN RANGÁRÞING EYSTRA [3].

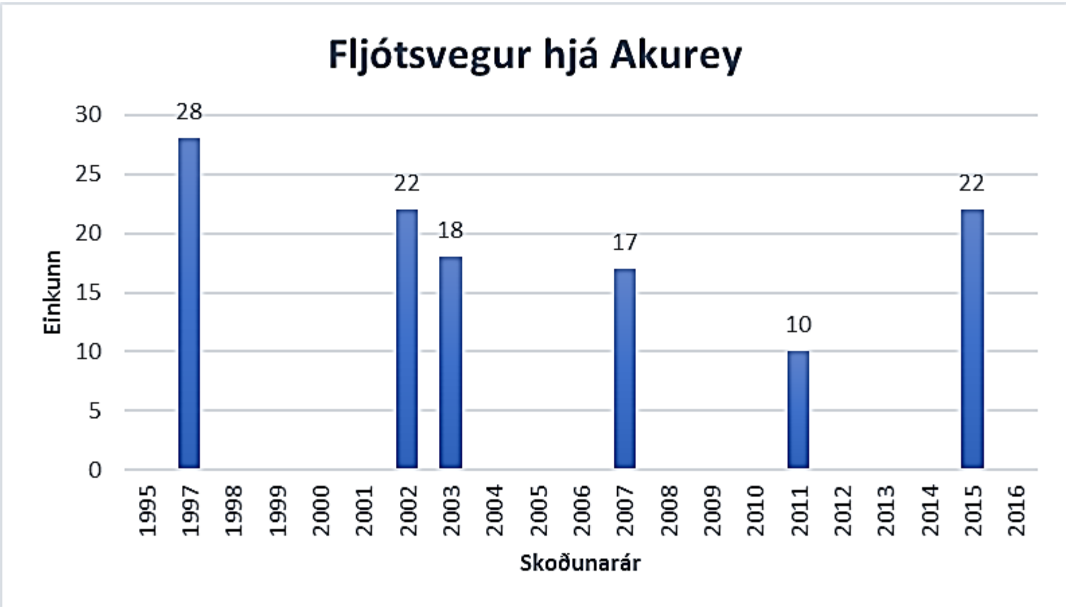

FIGURE 2-4 - SUM OF THE GRADES FOR EACH INSPECTION, FLJÓTSVEGUR BY AKUREY IN RANGÁRÞING EYSTRA [3].

Comparison to the authors' methodology

The authors of the current research are proposing a different point of view for grading a bridge. Because of the different inspection dates, and because of the different components inspected during the last inspection, the authors believe that the sum of the grades as a final grade for the single bridge is unfair. To the authors, an average for all five bridge components must be implemented, and the final grade for the bridge must be the overall average of the five bridge components grades. This way a final bridge grade is a number between 0 and 5.

Taking as an example the same bridge examined by Guðmundur Úlfar and processing the data in a similar way, the authors found the following table (table 2-2) and chart (figure 2-5).

Inspection [year]	***Foundation*** *100* *(Undirstöður)*	***Structure*** *200* *(Burðarvirki)*	***Superstructure*** *300* *(Yfirbygging)*	***Soil section*** *500* *(Jarðvegshlutar)*	***Accessories*** *600* *(Aukahlutir)*	***Overall bridge grade***
1997	(8+6+7)/3	2/1	1/1	0/1	4/1	2.80
2002	(6+3+5)/3	(3+2)/2	1/1	1/1	1/1	2.03
2003	(6+2+2)/3	2/1	3/1	2/1	1/1	2.27
2007	(3+3+3)/3	3/1	4/1	0/1	1/1	2.20
2011	(0+2+3)/3	3/1	1/1	0/1	1/1	1.33
2015	(5+2+5)/3	2/1	3/1	1/1	4/1	2.80

TABLE 2-2 - GRADES ON BUILDING SECTIONS, FLJÓTSVEGUR BY AKUREY IN RANGÁRÞING EYSTRA [3].

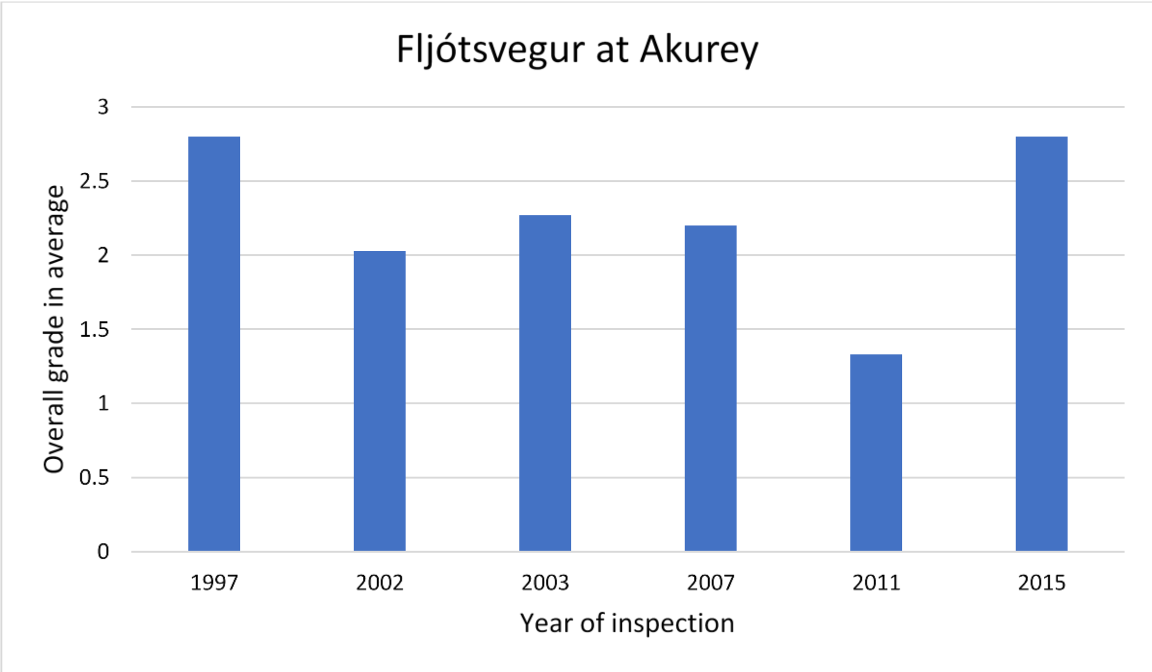

FIGURE 2-5 – AVERAGE GRADE FOR EACH INSPECTION, FLJÓTSVEGUR BY AKUREY IN RANGÁRÞING EYSTRA [3].

Even if figures 2-5 and 2-4 are similar, the authors of this paper prefer to work with the overall average because the grade range is always between the grading system. The reader, in the authors' opinion, can more easily understand the condition of a specific bridge and more easily compare different bridges. To better show the average method, the authors have found an interesting template from research conducted in Turkey in 2008 [9], adjusted to the Icelandic system (figure 2-6).

Bridge Name:

Construction Year:	**Inspection date:**	

MAIN BODY COMPONENTS				**EARTH RETAINING COMPONENTS**	
Deck		**Support**		**Abutment**	
Cracks		Metallic (M)/Elastometric (E)		Deformation	
Concrete Disintegration		Main Damage		Cracks	
Apparent Reinforcement		Support Bed		Concrete Disintegration	
Holes and Cavities		Lost of Elements (M)		Exposed Reinforcement	
Water leakage		Anchorage (M)		Holes and Cavities	
		Surface Arrangement E		Water and debris abrasion	
		Deformation E		Scour in foundation	
OVERALL GRADE		OVERALL GRADE		OVERALL GRADE	
Beams		**Piers**		**Approach Fill**	
Steel (S)/Concrete (C)		Deformation E		Settlement and Slump	
Deformation		Cracks		Erosion on Road platform	
Cracks		Concrete Disintegration		Erosion infill	
Rusting (S)		Apparent Reinforcement		OVERALL GRADE	
Bolts and Rivets (S)		Holes and Cavities		**Stabilization**	
Welding(S)		Water and debris abrasion		Settlement and Slump	
Concrete Disintegration		Scour in Foundation		Erosion	
Apparent Reinforcement				Scour in Bed level	
Holes and Cavities					
OVERALL GRADE		OVERALL GRADE		OVERALL GRADE	

SERVICEABILITY COMPONENTS

Coating		**Border- Railing**		**Expansion Joint**	
Waving		Border (B)- Railing®		Noise	
Tire tracks		Cracks in Concrete		Water leakage	
Cracks		Concrete Disintegration ©		Deformation	
Holes and Cavities		Apparent Reinforcement©		Holes and Cavities	
OVERALL GRADE		Deformation in Railing		Loss of elements	
Drainage		Rusting in Railing		Loss of function	
pipe damage		Deficiency in Railing			
Blockage		OVERALL GRADE		OVERALL GRADE	
Cleanout					
OVERALL GRADE					

ITEM	**OVERALL GRADE**
MAIN BODY COMPONENT (foundation+structure+superstructure)	
EARTH RETAINING COMPONENTS (soil section)	
SERVICEABILITY COMPONENTS (accessories)	
CUMULATIVE WEIGHTED GRADE	

FIGURE 2-6 – TEMPLATE BRIDGE INSPECTION BASED ON [9].

Methods and Material

Dr. Haraldur Sigþórsson provided the authors with a database from the bridge maintenance system institution, Vegagerðin. Not all information contained in the database was meaningful for the current research, so the authors decided to modify the database for this research purpose.

The database

The database from which all the following calculations and graphs are extrapolated, composed by 1146 bridges, is composed as follow:

- Identification number
- Name of the bridge
- Bridge length
- Age of the bridge
- Lane width
- Annual average daily traffic (AADT)
- Annual average summer traffic (AAST)
- Annual average winter traffic (AAWT)
- Last inspection date
- Average grade for the foundation components
- Average grade for the structure components
- Average grade for the superstructure components
- Average grade for the soil parts components
- Average grade for the accessories' components
- Overall grade

The main reduction from the database given by Vegagerðin is that in this research we are not considering previous bridge investigations, if not the very last inspection. Also, the authors have neglected all information about the type of road, the number of the road, the material composing all parts of the bridge, the specific inspection details, inspector notes. Every inspection of a component that falls into one of the five macro partitions of the bridge is counted as the average of the main part so that a comparison between bridges is fairer. As an example, the following table is reporting a sample of 20 bridges. In order to have comparable results, the overall average is done only on the components effectively inspected during the last inspection. If during the last inspection one of the macro partitions of the bridge was not inspected, the overall grade of the bridge is calculated not considering that specific macro partition. For example, if during the last inspection just the foundation part was examined, then the overall grade for the bridge is going to be just the average grade for the foundation part.

Bridge number	Name of the river	Bridge length (meter)	Age (year)	Lane width (meter)	AADT	AAST	AAWT	Last inspection	100	200	300	500	600	Overall grade
1740	Jökulsá á Brú hjá Hákonarstöðum	31.7	111	2.8				10/09/2014	2	1	0	0	0	0.60
767	Hrútafjarðará	24	107	7	41	64	25	27/08/2015	2	2			1	1.67
1742	Kaldá hjá Grófarseli	11.5	106	3				02/09/2015	10	12	2.5		1	6.38
1315	Munkaþverá	16	106	3.25	115	147	90	07/09/2016	2	2	3		4	2.75
1289	Garðsá í Ólafsfirði	8	96	3				11/09/2017	10	6				8.00
1298	Hörgá á Helguhyl	16.09	93	3.66				08/09/2016	2	2			1	1.67
1076	Sveðjustaðaá	7	93	3.65	10	16	5	17/08/2016	4	6	4		4	4.50
1076	Sveðjustaðaá	7	93	3.65	10	16	5	17/08/2016		6	4		4	4.67
1739	Hvammsá í Vopnafirði	18.5	92	2.7				05/09/2016	2	6	3		1	3.00
235	Hvítá hjá Brúarhlöðum	73.3	92	2.6	373	597	241	23/08/2017	3.33	3.5	4		1	2.96
393	Kiðafellsá hjá Kiðafelli	9	92	3.6	93	151	48	29/08/2017	3.5		2			2.75
799	Krossá hjá Gröf	12	92	3				09/10/2014	5	13	2			6.67
1318	Árbugsá hjá Þverá	16.8	91	3.2	56	95	27	08/09/2017	5.5	4				4.75
1435	Geldingsá	17.66	91	2.65	7	16	0	12/09/2017	9		8		4	7.00
1605	Hnefla á Jökuldal	9.5	91	3.2	12	26	4	02/09/2016	2	1.5	1			1.50
519	Hvítá hjá Ferjukoti	106	91	2.67	86	119	43	25/08/2015	3.33	3	1		1	2.08
964	Bjarnadalsá við Tröð	10	89	2.7				05/09/2018	16	11	8		4	9.75
1592	Hofsá í Vopnafirði	96.5	89	3.6	173	235	133	05/09/2016	5	10		2	1	4.50
1338	Laxá hjá Brúum	12.57	89	3.2	167	253	107	07/09/2016	4	3	4		4	3.75
1108	Svartá hjá Ártúnum	38	88	3.6	124	222	63	31/08/2017	2	2			2	2.00
1440	Syðri-Nesá	18	88	2.64	7	16	0	27/08/2013	6.5	9	8	2	4	5.90

FIGURE 3-1-– AN EXTRACT FROM THE ICELANDIC BRIDGE MAINTENANCE SYSTEM DATABASE, ARRANGED BY THE AUTHORS

The database has been manually computed and reduced by the authors of this paper in order to have the best tool for processing linear regression and extrapolate relevant information about the bridge status and the need for maintenance. After reducing the database to essential information, in order to investigate the cause-effect relationship between the data, the authors have decided to use a linear and non-linear regression methodology. Once again, Guðmundur Úlfar's words are going to illustrate the reader on this regression analysis process.

Regression analysis

The correlation analysis is conducted with the help of the Excel algorithm [3]. A point-chart is illustrating the relationship between a dependent variable (i.e. the overall bridge grades) and the different independent variables of the bridges (i.e. age, traffic, etc.); a correlation line (regression line) has been represented, along with the line equation and the R^2 coefficient of determination. A correlation line is a linear function of two variables (X and Y) and it is the line that best fits the data [3]. An $R^2 = 0$ means that the dependent variable cannot be predicted from the independent variable; an $R^2 = 1$ means that the dependent variable can be predicted without error from the independent variable; an $0 \leq R^2 \leq 1$ indicates the extent to which the dependent variable is predictable. An $R^2 = 0.10$ means that 10 percent of the variance in Y is predictable from X; an $R^2 = 0.20$ means that 20 percent is predictable, and so on [12].

Figure 3-2 visually explains the linear regression analysis [15]. The figure shows a graph of an *ad hoc* numeric set where the correlation line ($\hat{Y}$) and the average Y-variable ($\bar{Y}$) are brought in.

The point in the numeric library is outside the correlation line and it is removed on average (all points in the numeric set that are outside the correlation line), and the correlation line is used to construct the coefficient of determination (x_i, y_i) [3].

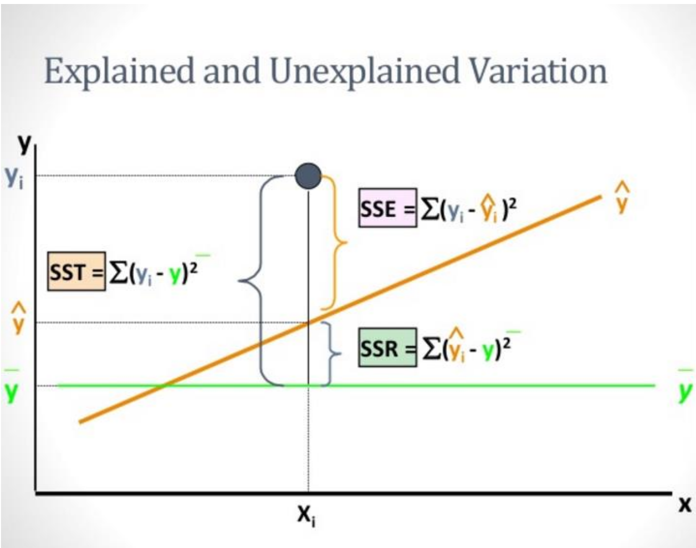

FIGURE 3-2 – EXPLAINED AND UNEXPLAINED VARIABLES IN THE LINEAR REGRESSION ANALYSIS [15].

The distances are defined by the following equations [14]:

1. SSE (sum of square error) is the variability of the unexplained variable

$$\sum_{n=1}^{i} \left(y_i - \hat{Y}_i\right)^2 \tag{3.1}$$

2. SSR (sum of square regression) is the variability of the explained variable

$$\sum_{i=1}^{n} \left(\hat{Y}_i - \bar{Y}_i\right)^2 \tag{3.2}$$

3. SST (sum of square total) is the overall variability

$$\sum_{i=1}^{n} (y_i - \bar{Y}_i)^2 \tag{3.3}$$

As an example, the unexplained variable could be the overall grade and the explained variable could be the age of each bridge (the age is given by the current year minus the year of construction). To put this all together in context, the following equation is presented:

$$SST = SSR + SSE \tag{3.4}$$

And then the coefficient of determination can be calculated by the following equation:

$$R^2 = \frac{SSR}{SST} = 1 - \frac{SSE}{SST} \tag{3.5}$$

The equation of the correlation line can be described as follows:

$$y = a + bx + \epsilon \tag{3.6}$$

Where:

1. y = dependent variable predicted (i.e. overall grade)
2. a = cutting point to Y-axis
3. b = regression slope coefficient
4. x = independent variable used to predict (i.e. age)
5. ϵ= unknown constant (it is a random variable with mean or expected value = 0) [13] [3].

A correlation test (Pearson's R) is implemented, which indicates the degree of correlation between the variables. The coefficient of determination takes effect in a range where 1 is the perfect correlation, 0 is no correlation, and -1 is a perfectly opposite correlation. The opposite correlation is determined by the regression slope coefficient of the correlation line. The correlation can be described by the following equation [16], given $-1 \leq R \leq 1$

$$R = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2} * \sqrt{\sum(y_i - \bar{y})^2}} = \sqrt{R^2} \tag{3.7}$$

It is important to stress the fact that a correlation R=0 does not mean zero relationships between two variables; rather, the result zero means that there are zero linear relationships between them. Curvilinear relationship, for example, can be strong between two variables even if those two have zero linear relationships [12].

For the non-linear relationships, the authors of this paper have implemented the logarithmic function on Excel. After selecting the data to be analyzed, under **Insert** in the Excel toolbar the authors selected the **scatter chart**; once the chart is created, trough the options for the **chart element**, the **trendline** has been selected; among the options of the chart, the authors selected the **logarithmic** trendline because it is the trendline that best visually represents the data. The authors must stress the fact that in order to have meaningful results, the database had to be reduced even more; all the bridges that were missing information about the traffic volume had to be not considered in the calculations.

$$\ln Y = \ln A + bX + \ln u \tag{3.8}$$

Where:

1. Y= dependent variable
2. A = cutting point to Y-axis
3. b = regression slope coefficient
4. X = independent variable
5. u = the model's error term

To use the non-linear formula, the authors of this paper have decided to take the logarithm on both side of equation 3.6; the reason is that by doing that, a linear regression can be used on the transformed data to obtain the necessary values (equation 3.8). Equation 3.8 has logarithms in it, but they relate in a linear way.

For the multiple linear regression, the authors have used the following formula [17]

$$y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \cdots + \beta_p x_{ip} + \epsilon \tag{3.9}$$

Where, for $n = i$ observations:

1. y_i = dependent variable
2. x_i = explanatory variables
3. $\beta_0 = y - intercept$ = constant term
4. β_p = slope coefficients for each explanatory variable
5. ϵ= the model's error term (also known as the residuals) [17].

Results

Linear and Non-linear regression

The authors found, in the bridge database, several grades that are greater than 5 or 8; the grade has been implemented in the calculation without any change from the database. The following graphs represent the linear and non-linear regression analysis performed with the available data.

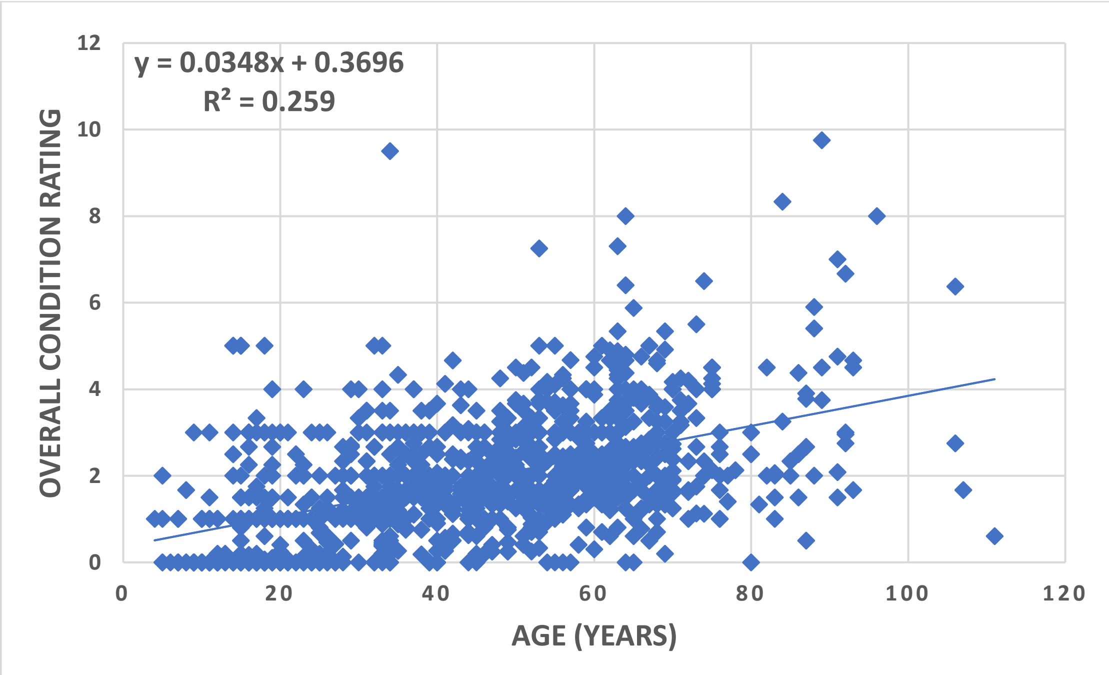

FIGURE 4-1 –OVERALL CONDITION RATING AND BRIDGE AGE

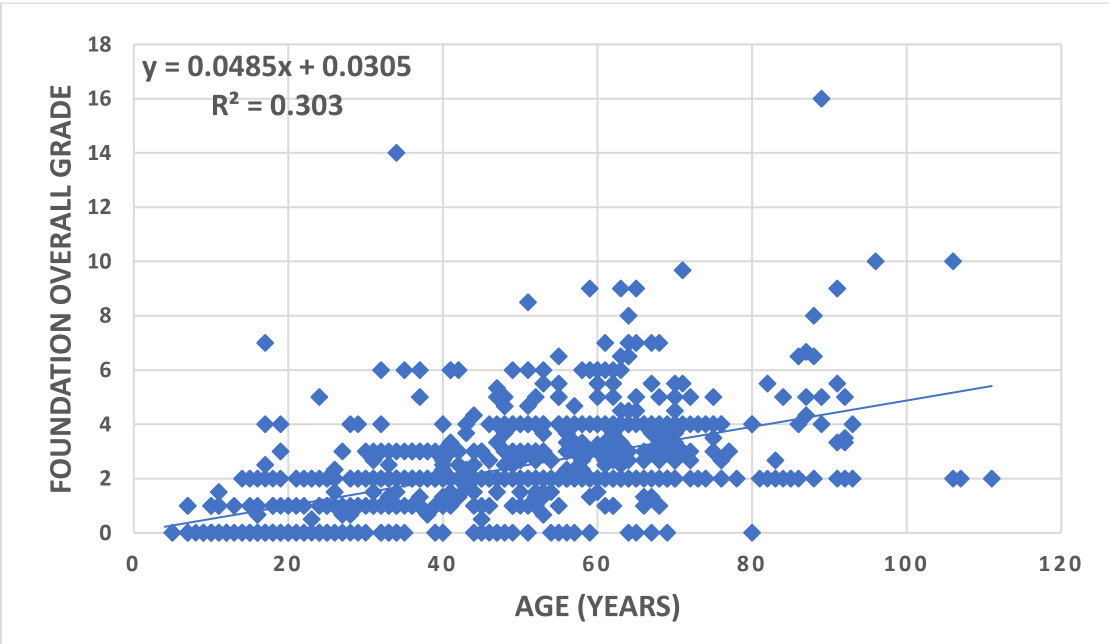

FIGURE 4-2 –FOUNDATION OVERALL GRADE AND BRIDGE AGE

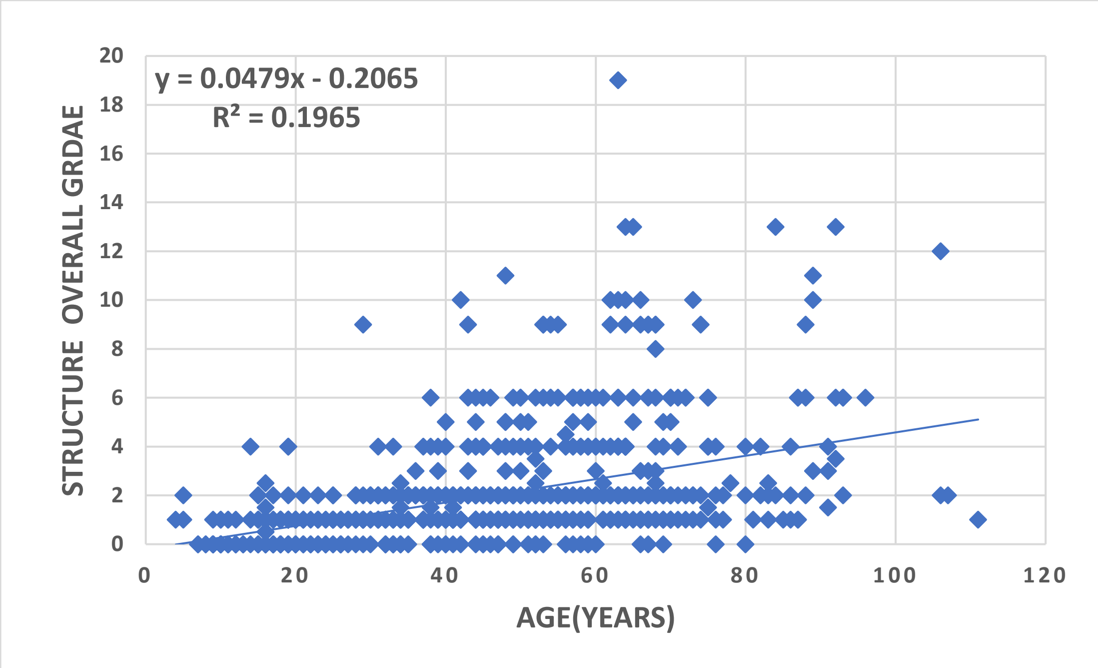

FIGURE 4-3 –STRUCTURE OVERALL GRADE AND BRIDGE AGE

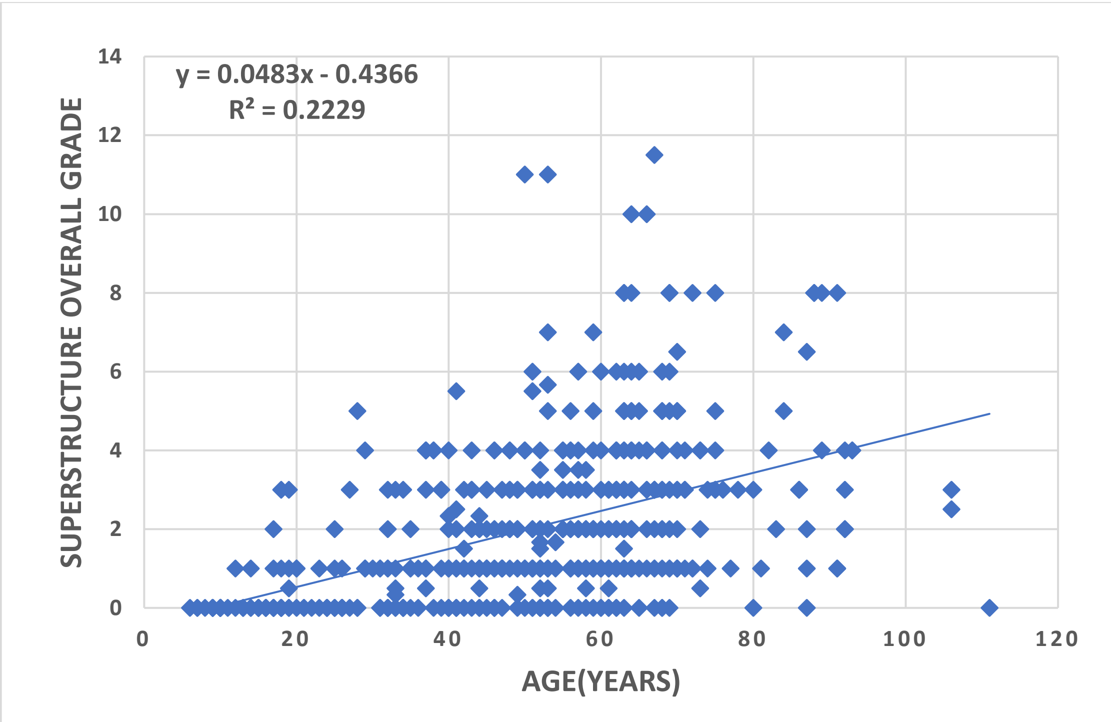

FIGURE 4-4 –SUPERSTRUCTURE OVERALL GRADE AND BRIDGE AGE

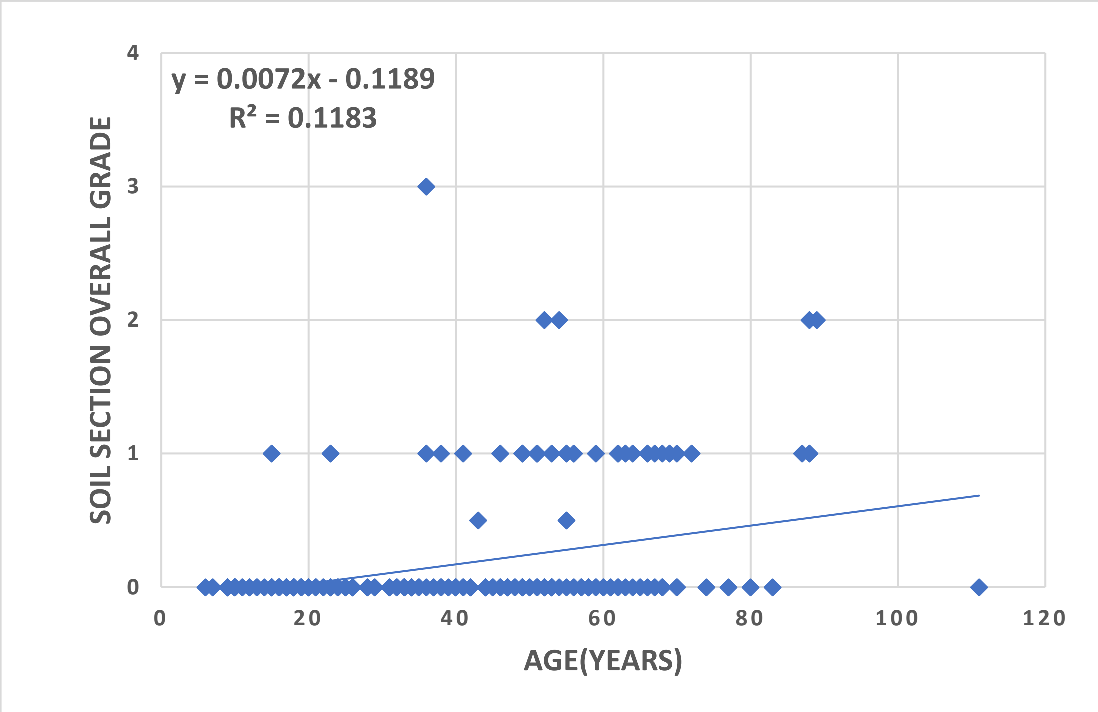

FIGURE 4-5 –SOIL SECTION OVERALL GRADE AND BRIDGE AGE

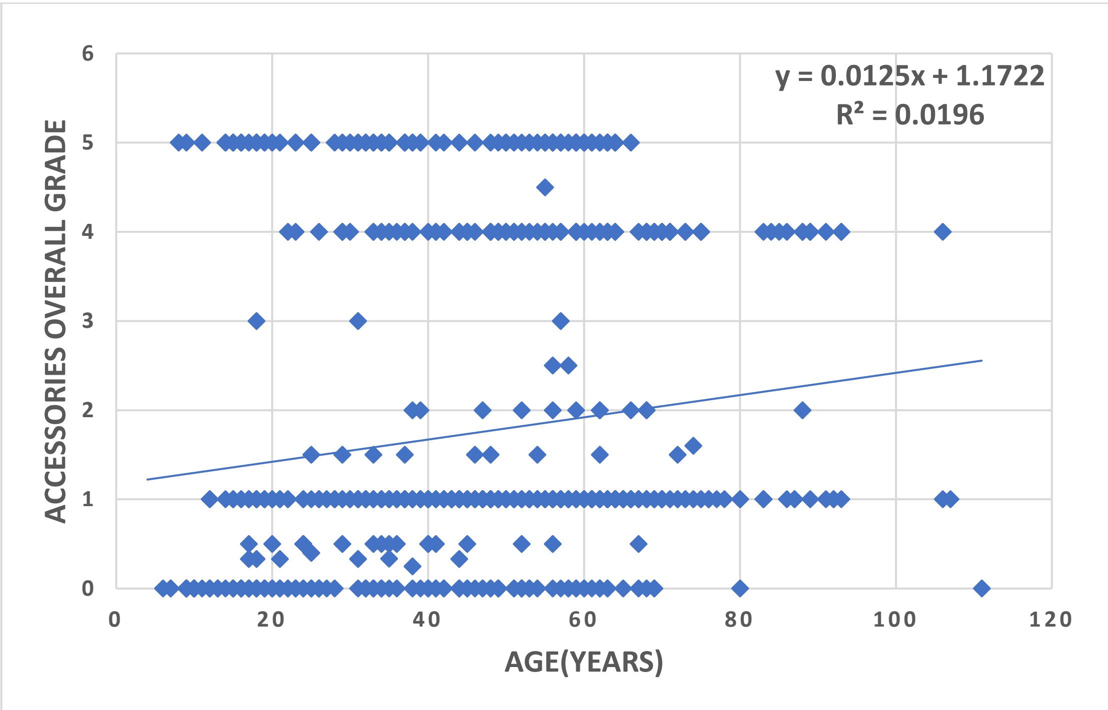

FIGURE 4-6 –ACCESSORIES OVERALL GRADE AND BRIDGE AGE

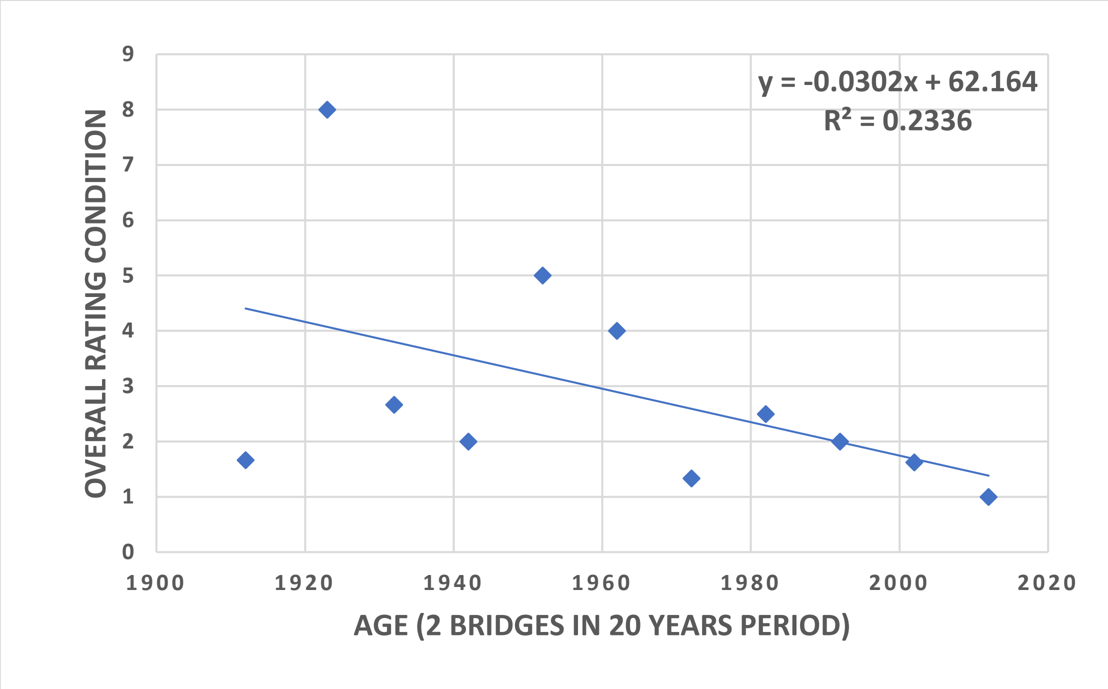

FIGURE 4-7 –OVERALL RATING CONDITION AND AGE (TWO BRIDGES FOR EACH TWENTY YEARS PERIOD)

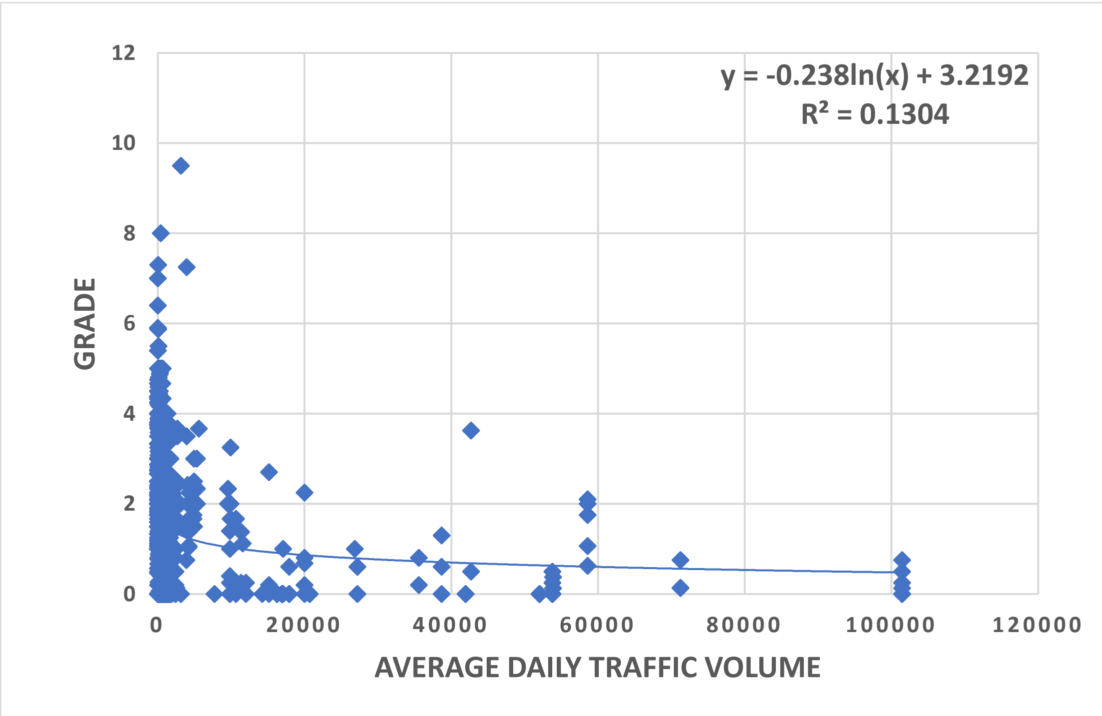

FIGURE 4-8 –AVERAGE DAILY TRAFFIC VOLUME AND GRADE

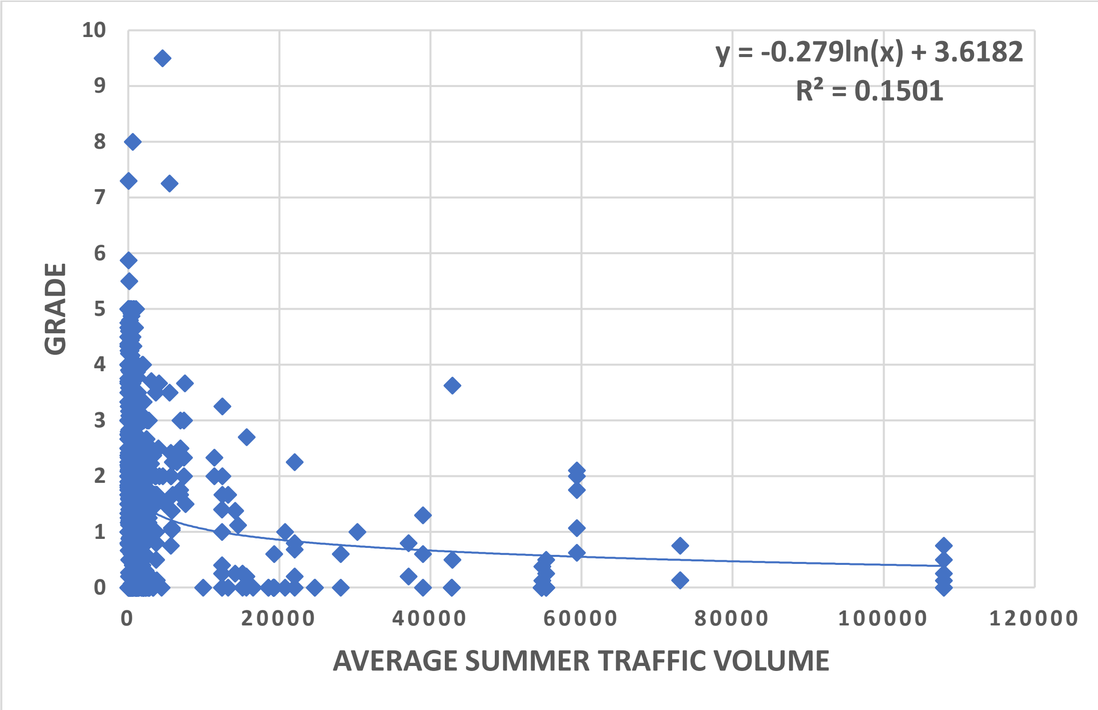

FIGURE 4-9–SUMMER DAILY TRAFFIC VOLUME AND GRADE

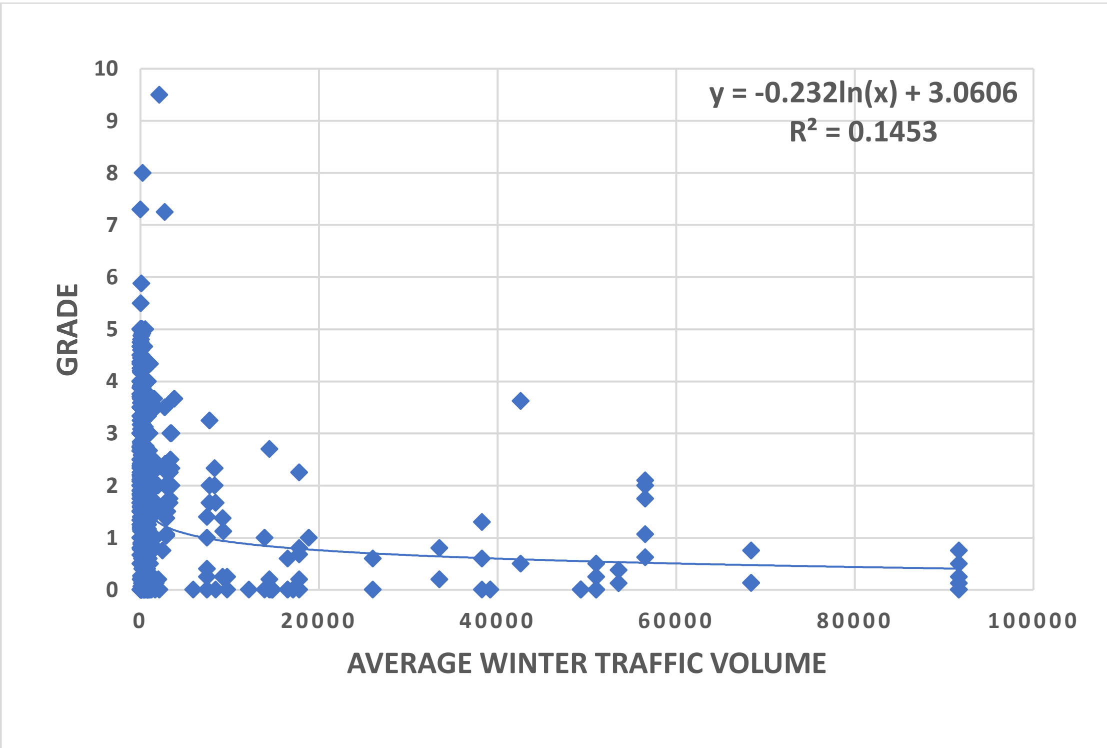

FIGURE 4-10 – WINTER DAILY TRAFFIC VOLUME AND GRADE

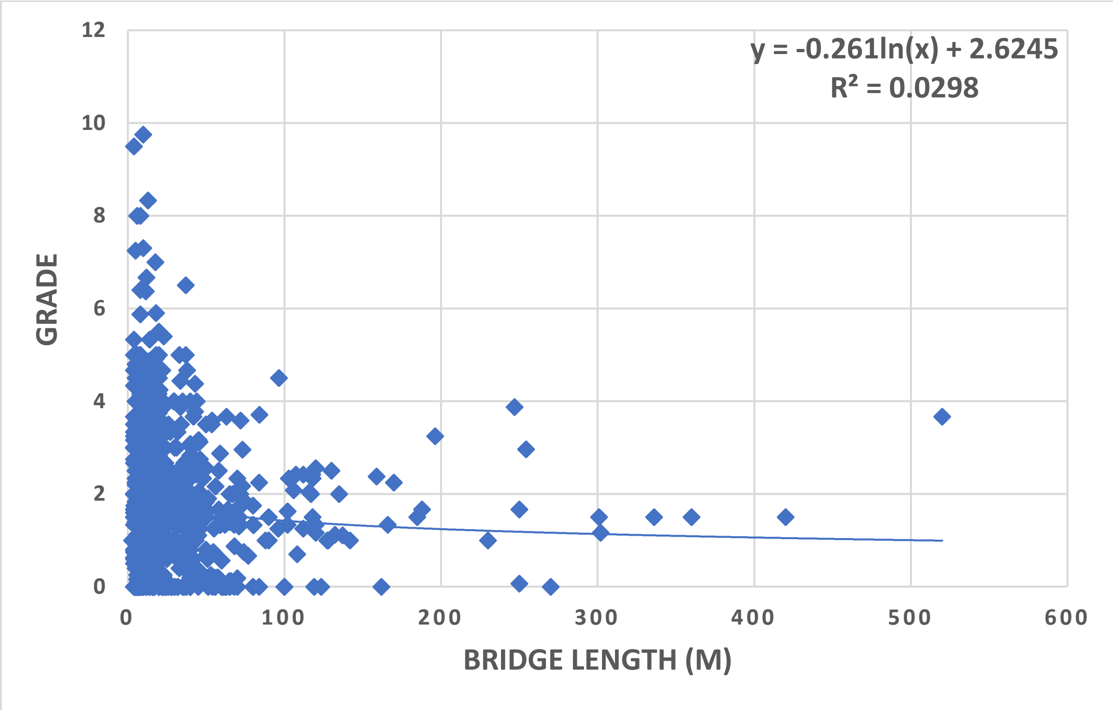

FIGURE 4-11 – BRIDGE LENGTH AND GRADE

Multiple linear regression

The authors have implemented the table below in Excel; using the **Data Analysis** from the tool bar, the authors have chosen the **Regression** from the menu and implemented the available data. On the Y axis the authors have selected the overall grade, on the X axis the authors have selected the age of the bridge, bridge width and the AADT; after selecting **Labels**, it is needed to select an **Output Range** where the table will appear. The results of the multiple linear regression were the following (figure 4-12).

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.538094993							
R Square	0.289546221							
Adjusted R Square	0.287211762							
Standard Error	1.12771037							
Observations	917							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	3	473.2035552	157.7345184	124.0313857	2.19107E-67			
Residual	913	1161.09011	1.271730679					
Total	916	1634.293666						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.984210851	0.174607297	5.636710885	2.30961E-08	0.641532559	1.326889142	0.641532559	1.326889142
Age	0.028180783	0.002223761	12.67257481	5.10353E-34	0.023816505	0.03254506	0.023816505	0.03254506
Lane width	-0.052348962	0.01884169	-2.778358161	0.00557552	-0.089327016	-0.015370908	-0.089327016	-0.015370908
ADU	-1.1158E-05	3.76636E-06	-2.962538874	0.003130265	-1.85497E-05	-3.76625E-06	-1.85497E-05	-3.76625E-06

FIGURE 4-12 – MULTIPLE LINEAR REGRESSION OUTPUTS

Conclusion

The conclusions for this study are as follows:

- For the investigated 1146 bridges, the overall average grade was determined, from the oldest bridge (107 years) to the most recent bridges; the investigation was carried out for the soil part, the foundation, the structure, the superstructure, and accessories of each bridge. Results from correlation analysis, of the data available on the last inspection date, indicate that there is a significant correlation between the age of the bridge and the overall score. However, age only explains just over 25.9% of the total score when all bridges in the country are compiled.

- Of the five building blocks defined previously, the foundations have by far the largest impact on the results of the overall average grade. When the entire country is compiled, the foundation component weighs roughly 30% of the total. The superstructure component comes next in the sequence with 22% of the total; the structure component weights 19%; the soil section weighs only 11% of the total, while the accessories component contributes is just under 2%. See table from 4-1 to 4-6 in the result chapter.

- From table 4-7 it can be concluded that choosing randomly 2 bridges for every 20 years' time slot, from 1908 until recent years, the final result, 23.3%, is similar to the one in figure 4-1, 25.9%.

- From figures 4-8 to 4-10, the annual average daily traffic (AADT), average summer daily traffic (ASDT), average winter daily traffic (AWDT), have a non-linear correlation with the overall grade; they respectively affect the grade with 13%, 15%, and 14.5%.

- The bridge length has a non-linear correlation with the overall grade of 0.3%, as shown in figure 4-11.

- From table 4-12 R square = 0.3, denoting a not strong relation between the variables taken into the calculations.

Discussion

The authors of this paper have found different outputs from the research carried out by Guðmundur Úlfar Gíslason [3] and similar research carried out in Turkey [9]. Among the possible reasons, the authors would like to point out the following:

- Difference between the sum of the grade's method, in contrast to the overall average method used in this paper [3].
- In the previous study, Guðmundur Úlfar only studied concrete bridges. The current research made no distinction between the bridges' construction materials [3].
- Because of the differences just pointed out with Guðmundur Úlfar approach, the results of the current research are not comparable with the results of Guðmundur Úlfar master thesis [3].
- In contrast with [9], in the current research, no distinction is made between the bridges (i.e. building material, concrete, steel, wood etc.), so that all bridges categories are implemented in the calculations. With this point, the authors want to stress the fact that a more specific analysis of certain bridge classes can lead to different results.

Furthermore, the authors of this paper would like to point out the following:

- One may not calculate the correct grade for a specific bridge if there are no periodic inspection or maintenance records; especially if the bridge's authorities select an as-needed basis for their repair or rehabilitation program rather than scheduled inspections. Regular bridge inspections are needed to perform a comprehensive analysis [9].
- If economically feasible, maintenance may be scheduled [9].
- The correlation between the final bridge grade and the AADT, ASDT, and AWDT was carried out on a small part of the database because of a lack of information. The insertion of the data regarding daily traffic in the BMS can improve the understanding of the correlation between traffic and bridge conditions.
- The Icelandic bridge management system is effectively assembled from three different database programs. For this reason, the authors think that a unification of the BMS in one unique program could improve the efficiency of the inspections, the effectiveness of the results and, furthermore, this can minimize the time spent working on the database.
- As previously indicated, the age only explains 25.9% of the overall grade for the Icelandic bridges; other factors influencing the final grade could be the subject of further research and could be an interesting continuation of this project. For example, the location could affect the final grade; both because of the material used in the construction (i.e. accessibility of quality raw material), the vicinity to salty water, etc.

- The authors of this paper decided to perform a linear and non-linear regression analysis in Excel. Improvements in the calculation could be done using a different and more specific statistical programming language (i.e. example R).
- A multiple linear regression analysis was performed in order to compare different contributions to the final bridge grade. The authors believe that in order to better understand the relationship between the dependent and independent variables, a multiple linear and non-linear regression must be implemented. The authors encourage further investigation and implementation of this analysis.
- The authors were not able to take into the multiple linear calculation more variables because of missing data, and because during last inspection the data was not uniform (lack of data regarding the single bridge).

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