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Development of a Locally Adapted Deterioration Model for Bridges in the State of Rhode Island, USA

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DEVELOPMENT OF A LOCALLY ADAPTED DETERIORATION MODEL FOR BRIDGES IN THE STATE OF RHODE ISLAND, USA

BY

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ABSTRACT

"One in nine of the nation's bridges are rated as structurally deficient" and Rhode Island is not an exception – 56.5% of the state's bridges are either structurally deficient or functionally obsolete [1]. Bridge Management Systems use prediction models to forecast the need of maintenance for bridges. Since those systems are based on general assumptions, it is of great interest to develop a locally adapted deterioration model to make those forecasts.

In this study, a Markov Chain based deterioration Model has been developed. It is based on condition ratings provided through the National Bridge Inventory. Additionally to the development of the probabilistic deterioration model, correlations to several items of the National Bridge Inventory were investigated to gain a better understanding what types of bridges have the most issues with deterioration. Maps were created to analyze the spread of deterioration factors in the state of Rhode Island. The maps can be used to visualize the data in a more approachable way for decision makers.

Additionally to the development of the Markov Chain based deterioration model, a short literature review for a more advanced model, the Bayesian Network, was given for future reference.

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CHAPTER 1

1. INTRODUCTION

The American Society of Civil Engineers (ASCE), conducts ever four years, an evaluation of the condition of the nation's infrastructure. In this study, critical parts of the infrastructure like bridges, roads, ports and dams are included. The in 2013 published *Report card for Americas Infrastructure* states, that America's grade in terms of infrastructure is D+. The nation's bridges are only rated slightly better with a C+, but by taking a deeper look into the numbers, even a C+ is not encouraging. "One in nine of the nation's bridges are rated as structurally deficient" and Rhode Island is not an exception [1]. In Rhode Island, 21.8% of bridges were deemed as structurally deficient. Adding functionally obsolete bridges, results in 56.5% of unsatisfactory bridge ratings. This grants Rhode Island the last place in a rating for the United States, followed by Massachusetts (52.5%) and Hawaii (43.9%) [2]. In the 2017 *Infrastructure Report Card*, the overall grade for bridges is still C+. The percentage of structural deficient bridges in Rhode Island increased to 24.9%, which still grants Rhode Island the last place in the ranking of all states [3].

Knowing these facts, it is not a question that something must change, but what is the best, given that an entire network of bridges within a state cannot be maintained overnight. Plans and decisions have to be made based on sound and objective data. Such data are stored in Bridge Management Systems (BMS), like the computer program Pontis, which is used by every Department of Transportation in the nation [4],[5]. BMS are not only supposed to store important data, they are also analyzing the data to support officials regarding their decisions. The analysis algorithms in Bridge Management Systems are universal, in order to account for numerous types of conditions.

In an attempt to gain a better understanding about bridge deterioration in Rhode Island, a locally adapted deterioration model is developed in this study. This model could help to improve decision making processes which are currently based on generic models as part of BMS.

The following sections will give a brief introduction to bridge management, bridge condition ratings and deterioration models.

1.1. Components of Bridge Management

1.1.1. Bridge Inspections

To obtain important data for bridge management, Field Bridge Offices have to conduct inspections for every bridge on a regular base. The interval for an inspection should not exceed 24 months. Regular base means for most bridges two years. If bridges turn out to have a lot of issues, are a sensitive part of the infrastructure or because of other numerous reasons, the inspection interval could be lowered to yearly inspections.

In order to maintain a continuous and precise record of the bridge, it is necessary to set up an inspection plan for every bridge and to follow certain techniques. Over the life span of a bridge the need for inspection changes and also the intensity of every inspections varies. *The Manual for Bridge Evaluation* defines 7 different types of inspections, which will be described hereafter [6]. In this chapter only basic types of inspections and their influence on bridge management will be discussed. Fracture-

Critical Inspections, Underwater Inspections and other special inspections are not part of this work because of their very specific nature.

Initial Inspections

As soon as a bridge is built, it has to be inspected before the first usage. This Inspection is called Initial Inspection and also applies for bridges which have changed in the configuration of their structure, for instance through widenings or lengthenings. In the case of the change of the owner this type of inspection should also be conducted [6].

The initial inspection pays attention to two topics: providing all Structure Inventory and Appraisal data (SI&A) and determining the structural condition of every structural member. For the determination of the structural condition of every member, the inspector has to identify and list any existing problems. In order to find every possible risk the inspector has to follow a strict plan [6].

Routine Inspections

Routine Inspections are conducted on a regular base, depending on the needs of the individual bridge. They consist of observations and measurements to obtain the physical and functional condition of the bridge accordingly to the requirements of the National Bridge Inspection Standards (NBIS). The purpose of routine inspections is to determine any differences from the initial or previously recorded conditions and to guarantee that the bridge still meets present service requirements. This applies not only to condition ratings (discussed in section 1.2) but also to parameters like average daily traffic (ADT) and average daily truck traffic (ADTT) since they are also subject to change [6].

Usually inspectors will conduct routine inspections from the deck, ground and/or water levels and from permanent work platforms and walkways. Any underwater parts of the bridge will only be observed during low-flow periods and will be probed for signs of undermining. Areas of special attention are determined by previous inspections or load rating calculations. Critical areas should be inspected according to the procedure described under “In-Depth Inspections”, which follows later in this chapter [6].

The results should be well documented with photographs of any area which has any problems shown as well as appropriate measurements. Additionally, a written report including recommendations for maintenance and repair has to be issued. If necessary this report contains recommendations for scheduling any in-depth or other special inspections. The report should also include a re-evaluation of the load capacity to verify if any structural condition changes affect any previously recorded ratings. [6]

Damage Inspections

A damage inspection is defined as an unscheduled inspection after a structural damage occurred, to determine necessary emergency load restrictions or even the closure of the bridge to traffic. The extent of this type of inspections depends on the cause and the dimension of the damage. The inspector has to evaluate every fractured member and to determine the extent of section loss and loss of foundation support. Additionally, the inspector should take measurements to obtain misalignment of members. In the case of severe damage, inspectors must be capable of making on-site calculations to determine emergency load restrictions. [6]

Damage inspections should be complemented by a short-term in depth inspection if necessary to verify the field measurements and calculations and to refine the established load or speed restrictions. The documentation of this inspection has to contain recommendations for follow-up procedures and it must exercise the awareness of the potential for litigation.[6]

In-Depth Inspections

This type of inspections are usually scheduled either independently from a routine inspection or as a follow-up of a damage inspection. Depending on the size of the bridge either the complete bridge can be examined at once or the bridge can be divided into segments which are examined individually. [6]

In-depth inspections require a close-up, hands-on inspection. Therefore, special equipment, such as under-bridge inspection equipment, staging and workboats are required. To maintain a high safety level for the inspector(s), special personnel to control the additional equipment is needed. The inspection includes the examination of all critical members of the chosen segment as well as nondestructive field tests, load tests and material tests. [6]

The report for in-depth inspections should include all results of the performed tests as well as photos of critical areas. Also the defined segments of the bridge have to be clearly identified in the report to ensure that no part is missing and that future inspectors will choose segments according to the first in-depth inspection. [6]

Planning of Inspections

A well-planned inspection is essential for the success of a good bridge management. Therefore, the inspector who plans the bridge inspection should consult the local highway maintenance superintendent, who may point out some important local condition changes over the year and give recommendations for a good time to inspect a certain bridge. Additionally, all items of the following points should be considered to conduct an effective and safe inspection. [6]

- Determination of the required type of inspection
- Define the need of personnel and equipment
- Review existing records to determine existing defects
- Estimate needed time for the inspection
- Coordinate the inspection with other agencies or public
- Compose field-recording forms and pre-drafted sketches of typical details
- Identify the need of underwater inspection and the vulnerability to scour
- Decide which testing methods should be used
- Determine areas of special attention, such as fracture critical members, non-redundant members and fatigue-prone details
- Identify nearby structures which need similar inspection personnel and equipment

The inspection should be scheduled in a period of the year which offers the best conditions for an inspection of the entire bridge. Special attention should be given to bridges over streams or rivers. They must be inspected during a low water period to gain the best inspection result. For higher bridges, seasons with expected heavy winds or storms and extreme temperatures must be avoided. [6]

1.1.2. Bridge Files (Records)

Each bridge should have a bridge record including all important information since it was built. That involves every record which was made for any repair, rehabilitation or replacement. In total, the bridge record should give a complete history about details of any damage and all strengthening made to the bridge.

In this section a brief overview about single parts of a bridge record will be given, starting with general parts and ending with very specific data which have to be stored digitally in the correct format according to the *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges*.[6]

Beginning with the planning process for a new bridge, construction plans, shop and working drawings and "as-built" drawings have to be added to the bridge record. All plans and drawings should be readable and available in an appropriate format. If the bridge record is stored electronically and in paper format, plans and drawings have to be cross referenced. In case of digital plans the responsible person should make sure to store the original files protected against changes and in appropriate formats to reuse them in the case of rehabilitation or replacement.

Not only structural computations and drawings have to be provided within a bridge record, but also pertinent material certificates, such as concrete delivery certificates, steel mill certificates and other manufacturers' certifications, must be included. In addition, to those certificates, material test and load test data can supplement the bridge record.

The recorded building progress in form of daily logs, memos, notes and pertinent letters should be included in the record. The As-Built-Status of the bridge should be documented by at least two photographs: one top view of the roadway and one side elevation view of the bridge. The record can be complemented by more photographs of any defects or areas of concern as applicable.

During the life span of a bridge maintenance and rehabilitation work will be done. A report for each work has to be attached to the bridge record in chronological order. It should include the date, description of project, contractor and other related data, such as coating history, accident records and flood data. Further information which should be included are traffic data, permit loads ("significant special single-trip permits issued for use of the bridge" [6]) and rating records.

The Federal Highway Administration (FHWA) has prepared special Structure Inventory and Appraisal (SI&A) forms to summarize required data to monitor and manage bridges within a BMS. The forms are based on the items defined in *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges* and include a tabulation of elements of interest about an individual structure. Their use is optional but highly recommended. An example for a SI&A form is shown in Appendix A. [7]

1.1.3. National Bridge Inventory (NBI)

The base for a good bridge management is, to have a detailed and consistent database of every bridge in each bridge owner's possession. All state Department of Transportation must prepare and maintain bridge records according to the NBIS.

With more than 100 entries, the *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges* defines every basic information which could be desired to evaluate structural health condition for bridges [7]. The following table gives a brief overview about the items used within the coding guide – these numbers are also used throughout this study to identify each item uniquely. A complete list can be obtained from the coding guide itself.

Table 1: Overview of defined items for NBI records [4]

Items 1–27:	General description and administrative information
Items 28–42:	Functional or operational (capacity) information, design load
Items 43–44:	Structure/design/construction type and material of construction
Items 45–56:	Span information, geometric information, and clearance dimensions (no Item 57)
Items 58–70:	Structural condition and bridge loading information
Items 71–72:	Waterway and approach data (no Items 73 &74)
Items 75–97:	Inspector's work recommendations and projected costs
Items 98–116:	Other information of various categories

Some of these data do not need to be updated, but some of them need to. In later parts of this study, items which need to be updated (condition ratings, average daily traffic (ADT), average daily truck traffic (ADTT), etc.) will be referred to as time-variant parameters. Items, which do not need to be updated (year built, location, structure ID, etc.) will be referred to as time- invariant. The exact coding can be found in the *Recording and Coding Guide for the Structure Inventory and Appraisal of the*

Nation's Bridges itself. In the following part only the most important items will be described in a general form.

Items related to structural components with operational characteristics need to be inspected by trained inspectors who must rate them following a specific rating system. For the rating of the bridge deck, superstructure and substructure, a schema from 0-9 is used. Bridges with very good conditions would be rated as 9, failed bridges as 0. If a rating is not applicable for a single bridge, N would be the appropriate rating. The objective of the NBI condition rating system is to provide an overall characterization of the general condition of the bridge by comparing the existing to the as-built condition. Any load bearing capacity shall not be used to describe the overall condition of a bridge since the fact that bridges were designed for different loads than nowadays, does not influence the overall condition of a bridge. [7]

Items 58, 59 and 60 (Deck, Superstructure and Substructure) are the main items of the NBI condition rating, which are under investigation in this study. Concrete decks should be inspected with special attention towards cracking, scaling, chloride contamination, potholing and depth failures. During the inspection of steel grid decks, special attention should be payed for cracked welds, section loss and corrosion. Item 59 (superstructure condition rating), is rated according to signs of distress, cracking, deterioration and misalignment of bearings. The substructure, described through item number 60, is rated regarding its condition in terms of section loss, misalignment, scour, collision damage and corrosion. [4]

1.1.4. Bridge Management Systems (BMS)

BMS were developed in the US for the first time in 1989 by six state DOTs on a project sponsored by FHWA. The object of that project was to develop a network-level bridge management system. The result of it was the computer program Pontis®, which is currently broadly used by transportation agencies. Another BMS which supports agencies is BRIDGIT™. It meets FHWA and AASHTO guidelines and can give network-level based recommendations. Both systems are considered as national systems. Their generic design provides flexibility, so it can be adapted to individual needs of State Departments of Transportation.

Performing bridge management requires a lot of data for every single bridge. To work with these data efficiently, a computerized tool (Bridge Management System, short: BMS) should be used. A BMS helps bridge program decision makers by storing data in one place, and provides analytical support. Although a BMS provides helpful analytical tools and can make recommendations for maintenance schedules, it should never be seen as a decision maker by itself. A good way to support bridge engineers with their decisions, is to run several what-if scenarios and make decisions based on them. For example, already scheduled maintenance actions could interfere with the one which is about to be scheduled. A BMS could identify such interferences and give recommendations for more appropriate time-periods.

Most likely, a BMS includes not only NBI relevant data, but it can contain much more detailed information, like inspection records, photos or drawings. Which information a BMS ultimately stores depends on different factors among the decision makers within an agency. Different approaches to planning, programming and budgeting, individual characteristics of the transportation system of each agency and also the political environment can influence the stored data.

In general, a BMS contains the following components [4]:

- Database,
- Data Analysis Tool and
- Decision Support [6].

Without a well-structured database, a BMS cannot work properly. Therefore, every BMS should include at least a bridge inventory and condition-, rating-, cost-, preservation-, and improvement-activity-data. These data are necessary to improve long- and short-term decisions regarding a healthy transportation network and financial constraints. [6]

1.2. Bridge Condition Ratings

The focal point of the decision process are bridge condition ratings, which are recorded according to the *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges* [7]. The bridge data is stored within more than 100 numbered items, grouped by categories: identification, structure type and material, age and service, geometric data, navigation data, classification, condition, load rating and posting, appraisal, proposed improvements and inspections. Data which are not subject to change (time invariant data) work as a filter to ensure a consistent database. The sorting and verification will be explained in section 2.1. Data which are subject to change (time variant data) will be investigated regarding their behavior over time and their correlations to other items. Deck condition, superstructure condition and substructure condition (items number 58, 59 and 60) are considered for an in-depth investigation. Part of the investigation is to find correlations between each of the named items, as well as correlations to a number of other items. The process of finding correlation factors will be described in section 2.2.

The data utilized in this study can be found in several categories, the order of numbering is random and does not matter for the research itself. However, for a better reference the item numbers will be used next to the name of each item. An overview for items is enclosed in Appendix A. To name some items: structure number (item 8) and latitude and longitude (item 16 and 17) can be found in the category identification. Structure type (item 43) though, can be found in the section structure type and material. Appendix E shows every time-variant and time-invariant item which is used in this study. Also, it shows the content of each item as well as the meaning of different ratings.

1.3. Deterioration Model

To describe deterioration, a mathematical model is needed. In this study the Markov Model is used and the Bayesian Network approach is discussed. The Markov Model uses a probability matrix and an initial state matrix to predict future conditions [8]. Hence, the model uses just one initial state to calculate further states – which makes the model easier to build and to compute. To handle a large number of dependent random variables at a time, Bayesian Networks can be used. Bayesian Networks use other common probabilistic models to describe the deterioration process, like the Markov Model, but it can combine different steps or cases with each other [9]. Both approaches will be discussed in Chapter 2.3 but only the Markov Model will be applied.

CHAPTER 2

2. METHODOLOGY

The heart of this study is the bridge condition rating published by the Federal Highway Administration [10]. Those bridge condition ratings are coded files, which are available for every state within the United States from 1992 to 2016 [10]. The file format is defined in the *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges* [7]. According to this defined format, the data are imported into one excel spreadsheet document and are evaluated as described below.

In 2.1, the first step of processing the data is described. The data are sorted to ensure consistency by removing bridges for different reasons. Next, section 2.2 outlines how the data was analyzed and how correlation factors between different items were computed. Section 2.3 provides the reader with information on how the deterioration model was developed.

2.1. Filtering

After downloading all bridge records for Rhode Island, all files were imported to a single excel spreadsheet. As a first step, every existing structure ID had to be collected and stored to get an overview how many datasets can be obtained. All structure IDs were then stored within one sheet, along with items of interest, such as condition ratings or year built. Table 2 shows in detail which and why items were used for filtering. Based on observations of those items, datasets were excluded from further investigations to ensure data consistency. To be removed, datasets must have less than four consecutive inspection records, an average time period between two inspection records of less than 2.5 years, or missing parts of the condition rating. Considered as a missing part are either blanks within a dataset or – most likely for condition ratings – the value 0 as a entry for one item. If a bridge is rated 0, the structure has failed. As an investigation of the available datasets has shown though, for a rating of 0, usually satisfying ratings were preceding. That and other observations, which will be discussed in chapter 3.1, was causing concern about the credibility of the data and therefore they were excluded.

Table 2: Items which are used for filtering

Item	Contribution to consistency
#43 Structure Type	Only bridges are evaluated, culverts are removed.
#58 to #60 Condition Ratings	Those items must have valid values (rating from 0 to 9) in order to contribute to the computation of valid correlation factors. N (not applicable) is a not valid value.
#90 Inspection Date	To develop a precise deterioration model, timespan between to inspections should be constant. If the average timespan between two inspections is longer than 2.5 years, the bridge was removed.

2.2. Data Analysis and Correlation Factors

In a similar study by Cruz for several states [8], bridges were divided into bridges with and without maintenance. This was done, due to increasing bridge deck ratings which does not reflect the real deterioration – ratings should decrease. Therefore, the deterioration factor for bridges with maintenance was computed taking all instances of bridge deck rating into account. The deterioration factor for bridges without maintenance was computed by excluding all instances where the bridge deck rating increased [8].

The datasets in this study were not divided into bridges with and without maintenance. This decision was made because of the following reasons. First, Cruz did not state an exact threshold how to differ between bridges with or without maintenance. That made it impossible to verify the correctness. Second, attempts to do this division by analyzing the deterioration factor failed. More information about this is provided later in this section. The third reason lies in the filtering process itself. Over 60% of structure IDs provided unusable data (see 3.1) which left a small number of valid datasets. This small number of datasets could be evaluated by hand to gain the most exact result. Deterioration factors were computed for bridge deck, substructure and superstructure separately. The following sections describe the examination and computation process in detail.

In general, a deterioration factor is computed according to (1) which shows the unit of deterioration: $\frac{1}{year}$. For simplifying reasons, the unit of the deterioration factors is not displayed. If a bridge has a superstructure rating of 9 (excellent condition) and a deterioration factor of -0.125, that means that the bridge would need 8 years to decrease to a rating of 8 (very good condition).

$$Deterioration\ factor = -\frac{rating_i - rating_n}{n - i} \tag{1}$$

Figure 1 shows an illustrative example for a condition rating. It is clearly visible that the rating decreases over time from 7 (good condition) to 5 (fair condition). After decreasing, the rating went up in 2002 due to service. Within the time-span of 2002 to 2016 the rating decreased again, this time from 8 (very good condition) to a rating of 5. Taking a general approach to compute the deterioration factor over all years and claim this bridge as a bridge with maintenance, the deterioration factor would be - 0.083.

The approach in this thesis is, to divide the ratings in up to three time-periods, compute deterioration factors for each period and ultimately calculating the average deterioration factor. In the case of Figure 1, two time-periods should be considered. First from 1992 to 2001 (decreasing by 2) and second from 2002 to 2016 (decreasing by 3). The deterioration factor for the first period is $\frac{-2}{9\,years} = -0.222$ and for the second period $\frac{-3}{14\,years} = -0.214$. Therefore, the average deterioration factor for this bridge is $\frac{(-0.222)+(-0.214)}{2} = -0.218$. As it can be observed, this method results in higher, but also more precise deterioration rates.

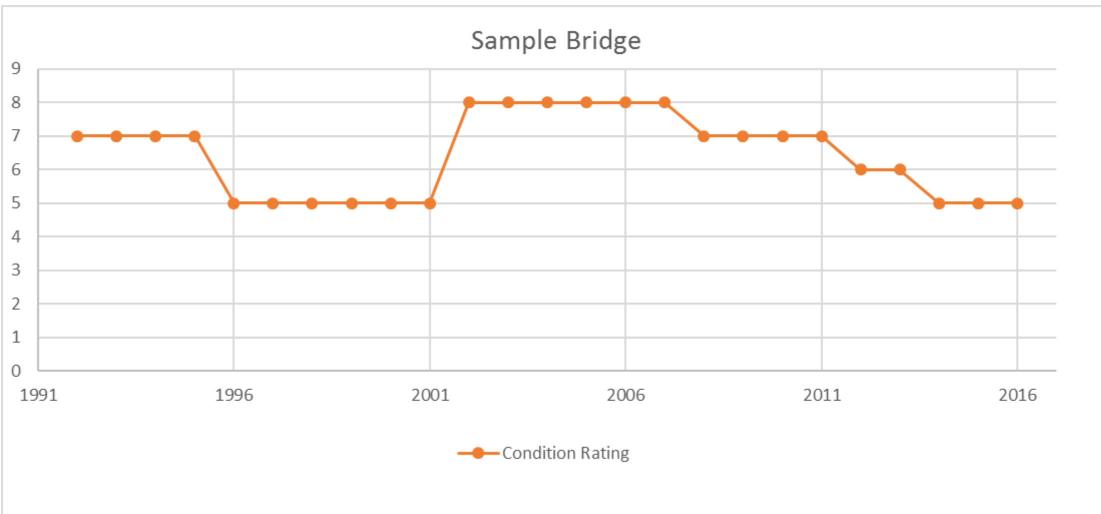


Figure 1: Sample condition rating

The boundary of this method is a maximum of three time-periods per bridge. One reason for this decision is, that bridges are usually only inspected every other year, which results in assumed ratings for every bridge in every other year. That virtually reduces the amount of available data. Higher inspection frequencies are possible but not considered within this computation. A second reason is that a higher rate of changing between ratings would result into non-representative deterioration factors.

An example for such a bridge is shown in Figure 2. There are just four consistent time-periods: 1993 to 1996, 1999 to 2003, 2004 to 2007 and 2011 to 2016. Since most of them are not longer than 4 years, just two real inspections possibly happened within each of them. That being said, this sample bridge would have to be neglected due to inconsistent data which could distort the results of the entire study.

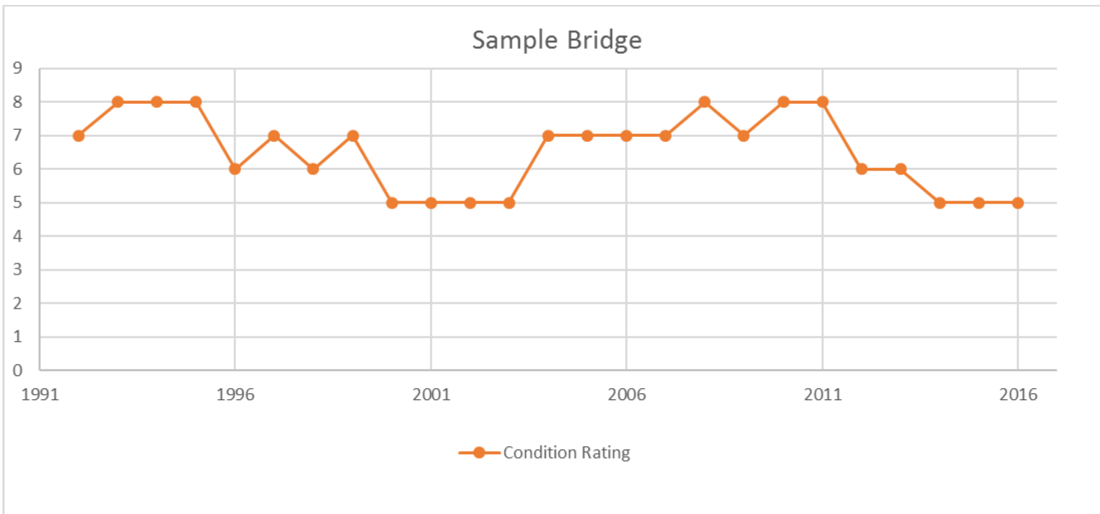


Figure 2: Sample of a neglected bridge due to its condition rating

In the multiple state study by Cruz, correlations between the bridge deck deterioration and time-invariant parameters were investigated [8]. In the present study, a similar approach is taken – the difference is, that more than just the bridge deck is under consideration. Based on the sorted data gained by evaluating the data according to Chapter 2.1, correlations between the deterioration of bridge deck, superstructure and substructure and several time-invariant as well as time-variant items are investigated. Listed in Figure 3 is every correlation, which is considered within this study.

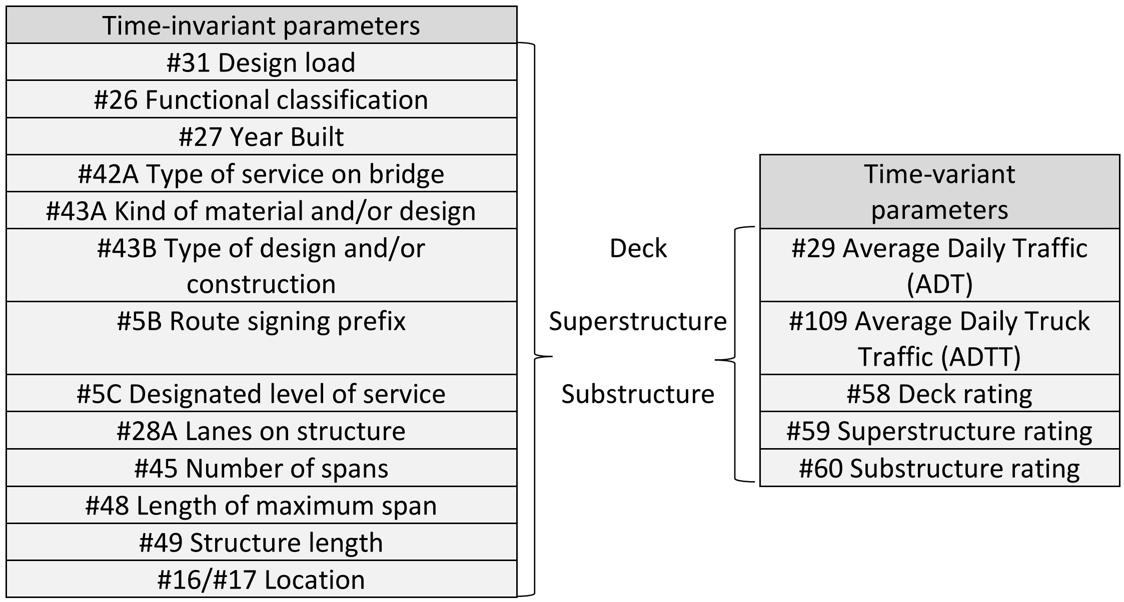


Figure 3: Possible Correlations

For investigating any correlations, the data is divided into three categories: bridge deck, superstructure and substructure. This had to be done, to be able to work with a maximum amount of data for investigations since some bridges had to be sorted out for the deterioration factor computation of just one or two categories. Bridges which were not valid for a deterioration factor computation were marked with the value '1000' instead of a deterioration factor in the relevant category, to make sure, that the dataset could still be used for the remaining categories. Showing in Figure 4, structure IDs 1970, 2430 or 2500 can be used for the computation and investigation of all three categories, whereas structure IDs 2040, 2490 or 2700 can only be used in one or two categories. A full list of bridges which are used for which category can be found in the appendix.

	Deterioration Factors		
Structure ID	Deck	Superstructure	Substructure
1970	-0.04	-0.04	0
2040	1000	-0.04	-0.04
2430	-0.04	-0.16	-0.20779221
2480	-0.04	-0.09191176	-0.04
2490	1000	1000	-0.04
2500	-0.0625	-0.0952381	-0.0952381
2570	-0.147	-0.09545455	-0.10964912
2600	1000	0	-0.04166667
2610	-0.0526	-0.04	-0.04
2670	-0.1429	-0.21428571	-0.07142857
2700	1000	-0.05555556	1000
2740	1000	-0.04	-0.07142857
2750	-0.0667	-0.06666667	-0.06666667
2760	-0.0812	-0.17045455	-0.08695652

Figure 4: Sample screenshot of bridges which could not be used for all deterioration factor computation

After dividing the datasets into the categories, the in Figure 3 listed items were stored next to the structure IDs into three different sheets to prepare the datasets for the next steps. All datasets were imported into MatLab to run curve fitting algorithms and create appropriate graphs for investigating correlations. The curve fitting algorithms were provided by the MatLab curve fitting toolbox [11].

Three different types of graphs were chosen as an appropriate way to show correlations between parameters. For discrete parameters such as design load, functional classification or type of service, box and whisker plots were generated. Non-discrete parameters, like year built, ADT or structure length are represented in scatter plots. If necessary, histograms are plotted next to those scatter plots were point overlapping is preventing a precise interpretation of the data.

For the investigation of correlations between the location and deterioration factors maps were created, using the ‘MyMaps’ feature of Google Maps.

2.3. Development Deterioration Model

After computing deterioration factors for each bridge, a deterioration model to predict future condition was developed. Deterioration can be defined as a random process where each incident is based on only the most recent previous incident – any other previous incidents are not considered [9]. In terms of this research, an incident is defined as the rating of a certain part of the bridge, during the most recent inspection.

In this section two different models will be explained. A widely used stochastic technique for predicting the performance of infrastructure is the Markov Model [12]. After discussing the Markov Model in section 2.3.1, another approach – the Bayesian Network – will be explained in section 2.3.2.

2.3.1. Markov Model

In a previous study regarding this topic [8], the Markov Model is used, since it is considered to be an straightforward model. Therefore, the Markov Model is also the approach in this study.

According to *Performance Prediction of Bridge Deck Systems using Markov Chains*, Markov Models are characterized by three advantages. First, they are able to reflect the uncertainty from different resources. Those different resources could be initial condition, applied stresses or the presence of condition assessment errors. The second big advantage is, that due to the computational efficiency, Markov Models can manipulate networks with many components. Also, they are incremental models, which accounts for present condition in predicting the future condition [12].

Morcous [12] stated in *Performance Prediction of Bridge Deck Systems using Markov Chains* that professional Bridge Management Systems use Markov Models as well, but they have some limitations which could affect the reliability of their predictions. One limitation is the constant assumed inspection period. In reality, this period is never exactly constant, in fact, it can highly vary depending on the severity of bridge conditions and relative costs and benefits. A varying inspection period results in not equally spaced condition data. Another limitation which was made to simplify the model is, to assume that the future condition depends only on present condition. Actually, deterioration is a nonstationary process where "time elapsed in the initial state affects the probability of transition to the following state" [12].

To keep the straightforward manner of the Markov Model, the same limitations as for professional Bridge Management Systems are applied for the purpose of this study. First, a constant inspection time interval is assumed and second, the bridge condition only depends on the most recent bridge condition and is defined as a numerical expression. Those limitations could be eliminated partially by developing a Bayesian Network which will be discussed in chapter 2.3.2.

According to Morcous in his article for the *Journal of Performance of Constructed Facilities* [12], for building a deterioration model based on the Markov process, two parameters are necessary. The initial condition vector P(0) is represented by the most recent/present bridge condition rating. A second parameter, the transition probability matrix P, is represented by a (n x n) matrix, where n is the number of possible conditions. Each element of the transition probability matrix represents the possibility of a bridge component to change from state (i) to state (j). It will be developed by evaluating all available bridge condition ratings [8], [12].

The prediction of the future condition for a bridge component can be determined as follows[8], [12]:

$$P(t) = P(0) * P^t \quad (2)$$

where

$$P^t = \begin{bmatrix} p_{1,1} & p_{1,2} & \cdots & p_{1,n} \\ p_{2,1} & p_{2,2} & \cdots & . \\ . & \cdots & \cdots & . \\ p_{n,1} & p_{n,2} & \cdots & p_{n,n} \end{bmatrix}$$

and

$$P(0) = [p_1(0) \quad p_2(0) \quad \ldots \quad p_n(0)].$$

To develop the transition probability matrix, a probabilistic approach was taken. Preprocessed data of the observed conditions served as base for a frequency analysis for every possible transition. For the computation of the transition probability matrix, ratings were expected to either decrease, stay constant or increase. Therefore, it was not necessary to differ between bridges with maintenance and without maintenance or to neglect additional bridges because of too many changes of ratings like shown in Figure 2. Due to this assumption, the developed model is capable of predicting the actual behavior of bridges.

First, the data was arranged by years 1992 to 2016 as columns and bridge ID as the rows of a spreadsheet as shown in Figure 5. Since there are 10 different possible ratings (0 to 9) for each item – bridge deck condition, superstructure condition and substructure condition – 100 different possible transitions are conceivable.

The possible transitions were divided into 10 subcategories: each for one initial rating with 10 possible outcomes. For example, there is one category for an initial rating of 7 with the 10 possible outcomes of a transition to either a rating of 0, 1, 2, 3, 4, 5, 6, 7, 8 or 9. To compute the transition probability matrix, a counter for each possible transition was implemented. The rating for each item per bridge was observed over the years 1992 to 2016 and the appropriate counter would count the frequency of one certain transition for every listed bridge. To account for the two year inspection interval an additional If-clause was added to each counter. Just if two consecutive ratings were stated at two different dates the counter would recognize the transition. For this threshold item number 90, date of inspection, was used.

The counters of each section were then divided by the sum of all counters of each section to compute the probability of each transition. Figure 5 shows the process on three exemplary bridges with their ratings from 1992 to 2000 for one item. Underneath the rating, two sections of counters are shown. Below the counters, a part of an exemplary transition probability matrix is computed.

Bridge ID / Year	1992	1993	1994	1995	1996	1997	1998	1999	2000
250i	8	8	8	8	7	7	7	7	7
260i	8	7	7	7	7	7	7	7	7
270i	8	8	8	8	8	7	8	8	8

	Section 7				Section 8			
Counter	7-7	7-8	7-9	…	8-7	8-8	8-9	…
Frequency	11	1	0	…	3	9	0	…
Sum	12			…	12			…

	9	8	7	6	5
9	…	…	…	…	…
8	0	$\frac{9}{12}$	$\frac{3}{12}$	…	…
7	0	$\frac{1}{12}$	$\frac{11}{12}$	…	…
6	…	…	…	…	…
5	…	…	…	…	…

Figure 5: Example for computing the transition probability matrix

2.3.2. Bayesian Network

Bayesian networks (BN) are probabilistic graphical models which describe a set of random variables and their respective probabilistic dependencies [8]. They gained a lot of attention in medical applications and for other decision-making problems [13]. Its roots are in the artificial intelligence society [13]. The benefits of BNs are, that they are intuitive to build and can handle a large number of dependent random variables [9]. To explain the basics of BNs, an example inspired by Hulst [13] and Charniak [14] can be found in the following paragraph with illustrations in Figure 6 and Figure 8.

Considering a house with two students living in there. Both have different and variable schedules, so nobody ever knows exactly if the other housemate is at home. An indicator if somebody is at home is a car parked in front of the house. Both students have also a bike. Bikes would be parked in a shed and are therefore not visible from the street. Thus, a parked car in front of the house, does not guarantee that the other housemate is at home. The third parameter in this problem is the outdoor light. Often one housemate turns it on after arriving at home, to welcome the other housemate. But there is also the possibility that they just forgot to turn it off after both were at home. The related graph to this example can be found in Figure 6.

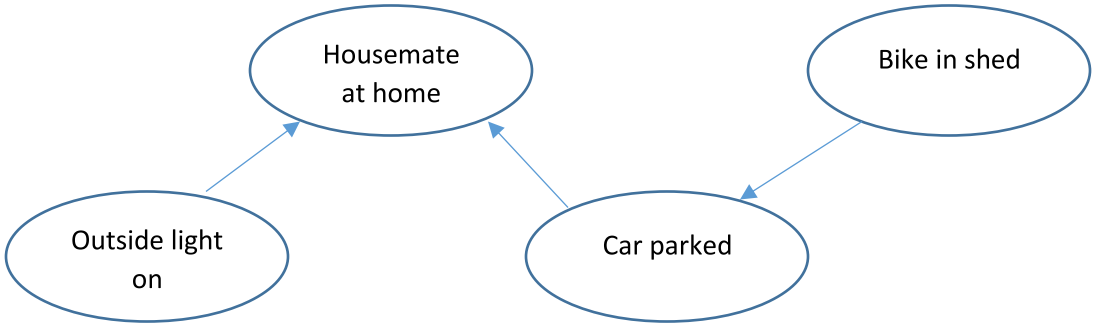


Figure 6: Simple BN student house

In *Modeling physiological processes with dynamic Bayesian networks* structure of graphs in BN applications is explained. A graph consists of two parts: nodes and edges, in the case of a BN edges are called arcs. There are two groups of nodes: parent-nodes and child-nodes. Within the student house example, the “Housemate at home”-node is a parent of the child-node “Outside light on” because it influences it directly. “Housemate at home” and “Bike in shed” are in this case so called root-nodes since they do not have any predecessors [13]. BN can be either linear, converging or diverging, as shown in Figure 7 [14].

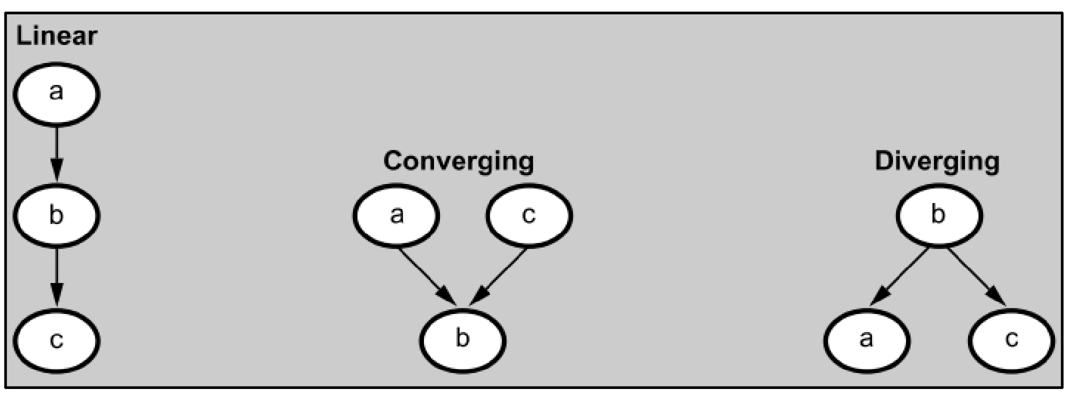


Figure 7: Connection types for BNs [14]

Those connections within a BN are possible according to Bayes' Theorem. Bayes' Theorem is stated in (3). In simple words it states that circles within BNs are not permitted [13].

$$p(X|Y) = \frac{p(Y|X) \cdot p(X)}{p(Y)} \tag{3}$$

The graph in Figure 6 shows the simple BN based on the student house example, but it does not help to find out if somebody is home yet. To be able to make that decision it needs the prior probabilities of all root nodes. Additionally, all conditional probabilities of non-root nodes with all possible combinations of their direct predecessors are necessary. Knowing those, a subset of the student house graph looks like as follows in Figure 8. The probabilities are randomly chosen for this example but need either to be calculated or estimated by experts for real scenarios [14]. A calculation of those values can be achieved by using for example the Markov Model approach from 2.3.1. The probabilities can be expressed within a condition probability table (CPT) [13]. The probabilities from the example are shown in a CPT in Table 3. As it can be observed, the nodes in the example can have two different states – either true or false.

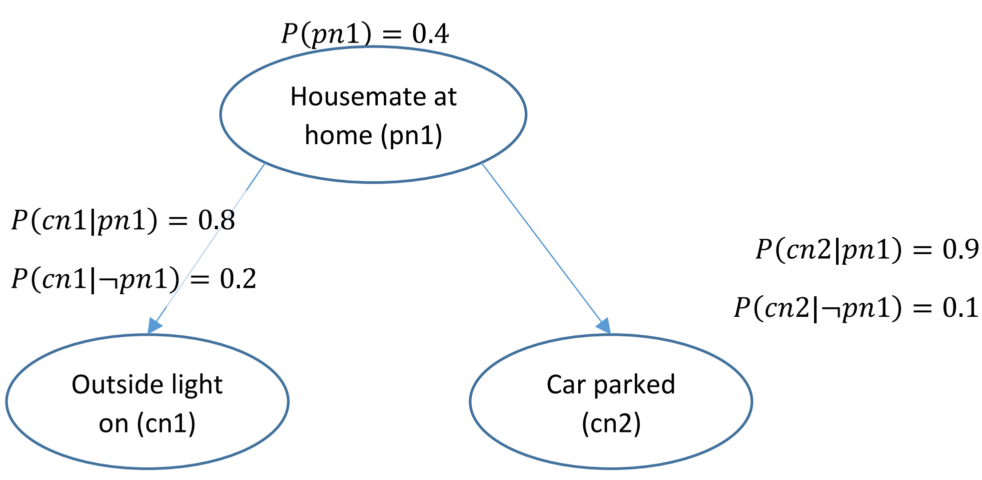


Figure 8: Simple BN student house with probabilities

P(cn1)	
True	0.8
False	0.2

P(cn2)	
True	0.7
False	0.3

P(pn1)				
P(cn1)	True		False	
P(cn2)	True	False	True	False
True				
False				

Table 3: Condition Probability Table (CPT) for the example

For some cases nodes need to have more than just those two possible states. Assuming a BN for bridge ratings. Bridge ratings in the national bridge inventory can have ten different states, ratings between 0 and 9. The size of a CPT can be determined by using (4), where r_i stands for states of the variable, r_j stands for states of the parent and n is the number of nodes [13]. According to (4), the size of the CPT for this simple case is already 1000 (r_j=10, r_i=10, n=2). It can by observed, that the size of CPTs grows exponential to the number of parent-nodes. Therefore, this number should be kept as low as possible [13].

$$size(CPT)_i \;=\; r_i \cdot (r_j)^n \tag{4}$$

BNs in general are great to use for static problems. By adding a time dimension to a BN, BNs can be used to model dynamic systems and are therefore called dynamic Bayesian networks (DBN). In DBN one tries to model probability distributions over a semi-infinite collections of random variables [15]. Only discrete-time stochastic processes are considered, a next time-step can be added once new observations have been made [15].

To not be misleading: neither certain parameters nor the structure of the network would change in a DBN. Changing of parameters or the network structure itself, are part of Bayesian learning which is beyond the scope of this thesis. Introductions to Bayesian learning can be found in *Modeling physiological processes with dynamic Bayesian networks* and *Bayesian networks without tears*.

CHAPTER 3

3. RESULTS

In this chapter, the results will be presented. Section 3.1 will evaluate the sorting process and the issues that occurred during this process. In 3.2 and its subsections, the reader will find the computed correlations between deck, superstructure, substructure and all previously mentioned time-variant and time-invariant items. Finally, section 3.3 will show the developed deterioration model.

3.1. Filtering Process

During the sorting process, several unusable datasets were found. Starting with obviously not usable data such as the rating of culverts, up to missing condition ratings within the datasets. Before sorting, data for 868 structures was available – after sorting out 522 datasets, only 346 datasets were left. Table 4 shows how many datasets had to be removed, and for which reason.

Table 4: Listing of not usable datasets and the reasons for removing

Reason for removing	Amount removed
The data refers to a culvert. Culverts are not part of this study.	147
Inconsistent condition rating. For some years, the dataset has a 0-rating which would indicate a failed structure. The data are not credible since most of the bridges which are removed for that reason have a rating above 5 in one year and in the next year a rating of 0. Also, bridges which have an N-rating (not applicable) are removed and counted in this category.	318
Inconsistent inspection period. Bridges should be inspected every two years. To account minor inconsistencies all bridges which have an average timespan between two inspections more than 2.5 years are removed.	26
Too less data. Bridges were built too recent than an appropriate amount of data could have been collected	31
Sum:	522

Special attention should be paid to inconsistent condition ratings. They are responsible for about 60% of removed datasets. It has also been observed, that most of the structure IDs, which were removed because of inconsistent condition ratings, are consecutive IDs. The cause removed data due to inconsistent condition ratings will be discussed in the following paragraphs.

Most of the data are not consistent, and due to concerns about the credibility of those datasets, they are removed. Taking structure ID 8370 or 3880 in Figure 9 as examples. Both are starting off with valid ratings in 1992, worst rating is for substructure with 4 (poor conditions) and 3 (serious conditions) respectively. In 1993 and 1994 the entire condition ratings as well as date of inspection (item 90) have a value of 0, called 0-rating. For the years from 1995 to 2005 no data were available for those bridges. From 2006 to 2010 they showed legitimate values for condition ratings. Even the date of inspection item showed that the last inspection was done in July 2003 which would suggest that data should have been available from 2003 on. From 2007 to 2016 no further data were available. This behavior can be found within many datasets and therefore they were neglected.

Year	RI92				RI93				RI94				RI95			
Bridge ID / Item	DECK_ COND_058	SUPERSTRUC TURE _COND_059	SUBSTRUCT URE _COND_060	DATE_ OF_INSPECT _090	DECK_ COND_058	SUPERSTRUC TURE _COND_059	SUBSTRUCT URE _COND_060	DATE_ OF_INSPECT _090	DECK_ COND_058	SUPERSTRUC TURE _COND_059	SUBSTRUCT URE _COND_060	DATE_ OF_INSPECT _090	DECK_ COND_058	SUPERSTRUC TURE _COND_059	SUBSTRUCT URE _COND_060	DATE_ OF_INSPECT _090
8370	7	7	3	292	0	0	0	0	0	0	0	0	#N/A	#N/A	#N/A	#N/A
8380	7	4	4	292	0	0	0	0	0	0	0	0	#N/A	#N/A	#N/A	#N/A

Figure 9: Sample of neglected dataset

One other observed behavior is N-rating. In terms of condition ratings within the NBI, N stands for 'Not applicable'. This rating has to be given if a structure is for example considered a culvert and has therefore neither deck, superstructure nor substructure. Taking structure ID 4200 as an example. It starts off with 0-ratings until 2006. In 2006 it is rated as N, although according to the records no new inspection has been done. The first valid ratings are recorded in 2007: ratings of 6 (satisfactory condition) to 7 (good condition). This first valid entry in the database also states that the last inspection happened in November 2005 which, again, suggests that ratings should have been available from 2005 and not from 2007. As an additional check for this specific bridge the year built item (item 27) was considered. This item states in the record of 2006, that structure ID 4200 was built in 1950. Another inconsistency which causes skepticism towards every single inconsistency in ratings in general.

Due this observed inconsistencies the entire database was searched again for small inconsistencies. Even those small inconsistencies – a single N- or 0-rating within a dataset – caused bridges to be neglected. During this in-depth search another inconsistent dataset has been observed. Structure ID 2430 showed for item number 28A, Lanes on structure, a very unusual value. In the bridge record available for years 1992 to 1994, the item stated that 24 lanes were situated on the structure. Taken this value as an obvious error, the real value was investigated by searching all other available dataset for this bridge. It turned out, that a real number of lanes on structure could not be determined. Between 1995 and 2013 the value was 6 and from 2014 on the number of lanes on the structure remained 4. According to the *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges*, even if lanes are closed due to load postings, they should still be mentioned as existing lanes. Therefor, this particular bridge had to be negelected.

3.2. Data Analysis and Correlations

In this section, the analysis-results are presented. It starts off with the results for the bridge deck, and goes on with results for superstructure and substructure. Each section will follow a certain pattern – describing the average deterioration factor, describing the correlation factors to certain time-variant and time- invariant items (cf. 2.2) and interpreting both of them.

3.2.1. Bridge deck

Average Deterioration Factor

Starting by evaluating the bridge deck deterioration rate, it became clear that the deterioration factors for most of the considered bridges do not differ too much from each other. As it can be observed in Figure 10, 153 of the bridges do have a deterioration rate between 0 and -0.06. Most of the remaining 166 bridges split up on slightly higher deterioration rates, 80 bridges show a deterioration rate between -0.06 and -0.09 and 43 bridges show a deterioration factor between -0.09 and -0.12. Only 9 bridges have a higher deterioration rate than -0.2, the highest deterioration factor is -0.2857. The average bridge deck deterioration factor is -0.0725. Due to too many changes of the rating from one year to another, 28 bridges had to be neglected.

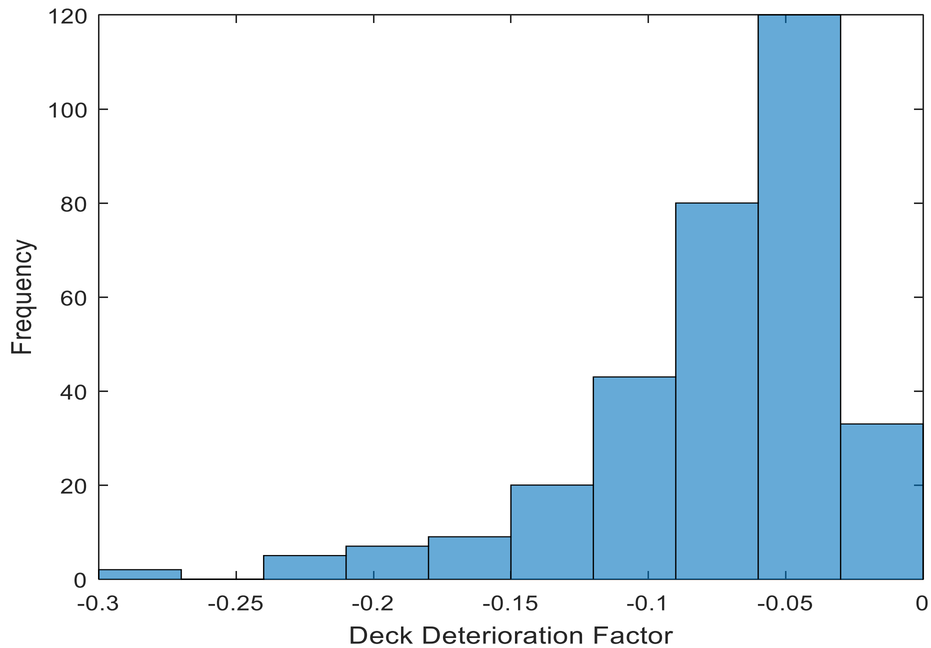


Figure 10: Deterioration rates bridge deck

Correlations to time-invariant parameters

This sub-section shows the results for possible correlations between the bridge deck deterioration and time-invariant parameters such as design load, functional classification of the road, structure kind, structure type, route prefix, service level, traffic lanes on bridge and number of spans in main unit. Since those parameters are discrete, box and whiskers plots were created. For non-discrete parameters scatter plots are more suitable for interpretation of the data.

During the analysis of the named data it became clear that correlations between the bridge deck and other time-invariant parameters are not very strong. In fact, the strongest correlation could be found between the deck deterioration factor and the year the bridge has been build. Figure 11 shows the related curve fitting – in Table 5, all computed correlation factors are stated.

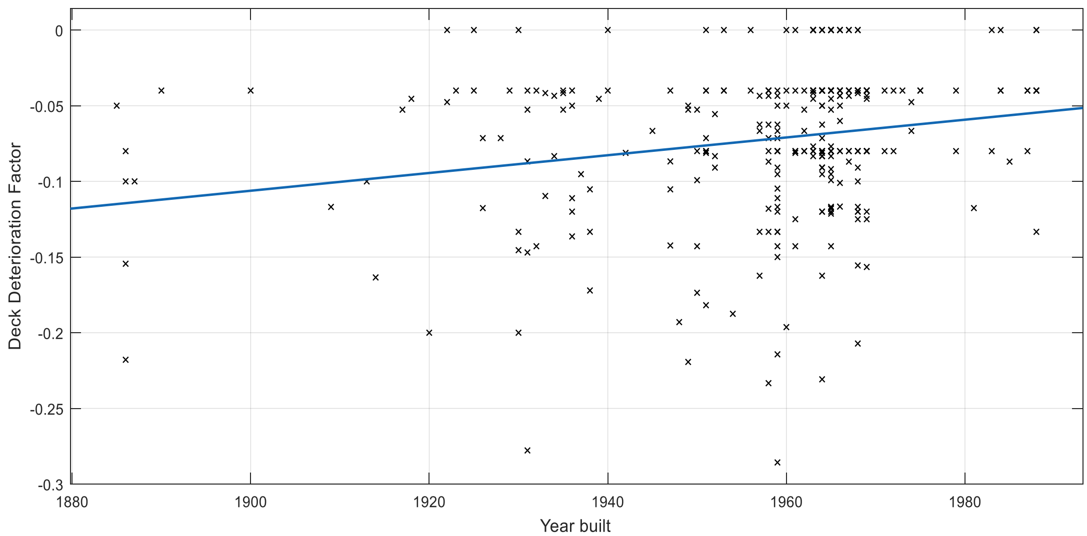


Figure 11: Correlation between Deck deterioration factor and year built

Shown in Figure 11, most bridges were built around 1960 and as seen in Figure 10, most of the deterioration factors are settled between -0.04 and-0.12. Remarkable as well is, that also bridges built in the 1880s have deterioration factors between -0.05 and -0.22 and not higher ones which one could expect.

Table 5: Correlation Factors for bridge deck deterioration to non-discrete time-invariant parameters

Parameter	R-square	R-square adjusted
Span length	0.01015	0.007024
Structure length	0.00067	-0.00249
Year built	0.04483	0.041817

All generated box plots for the bridge deck can be found in Appendix G. To show a general trend the box and whiskers plots show, the plots for design load, traffic lanes on structure and type of service on structure are shown in the following figures. The blue horizontal line shows the average deck deterioration factor of -0.0725.

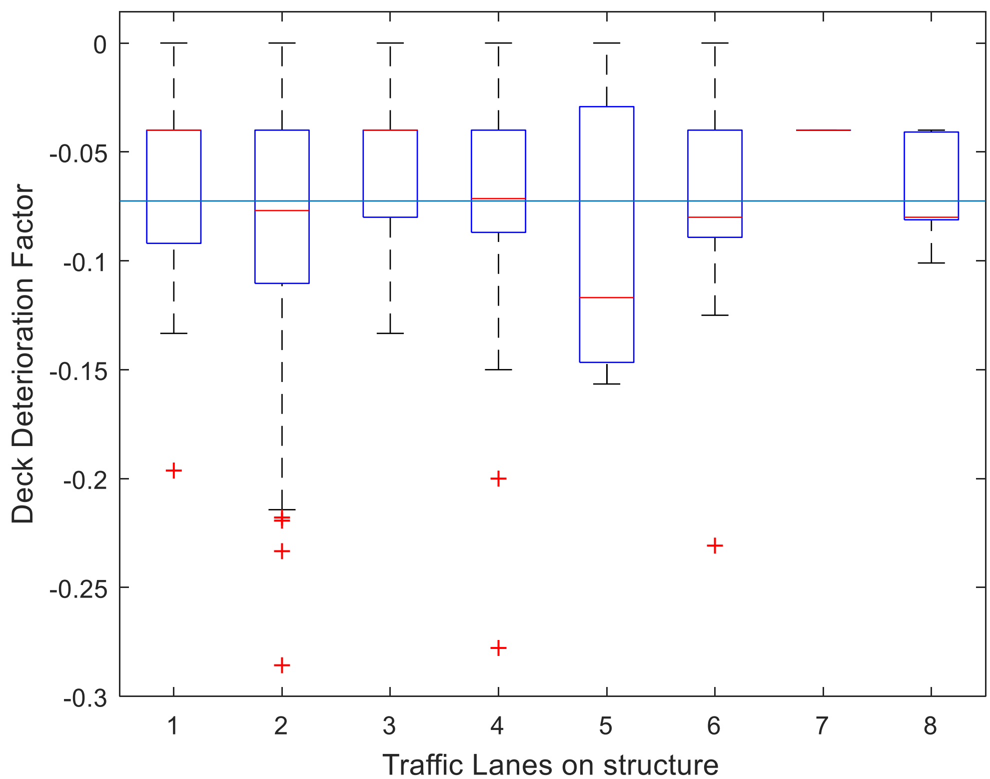


Figure 12: Box plot for Deck Deterioration Factor vs. Traffic Lanes on structure

The figure oben does not show a strong correlation between the parameters. An expected behavior could have been a higher deterioration rate for more lanes on a structure or even the opposite since more lanes on a structure could mean that a bridge is more important for the public so the maintenance intervals are shorter. The highest mean of deterioration factors can be observed for bridges with five lanes on them. One possible reason for such a higher deterioration rate could be an asymmetrical loading scenario which causes more damage to the structure itself than an even loading scenario. To find the real reason for this is beyond the scope of this study.

Shown in Figure 13 is the box plot for Deck Deterioration Factor vs. Design Load. As described in Appendix E, a rating of 0 stands for other or unknown design loads which makes it impossible to judge over this category. The average for categories 2 and 4 are higher than the overall average deterioration factor. In the categories of 5 and 6, the average deterioration factor is smaller than the overall average. Although in those categories there are more outlier than in other categories, the 75th percentile is lower than for categories 2 and 4.

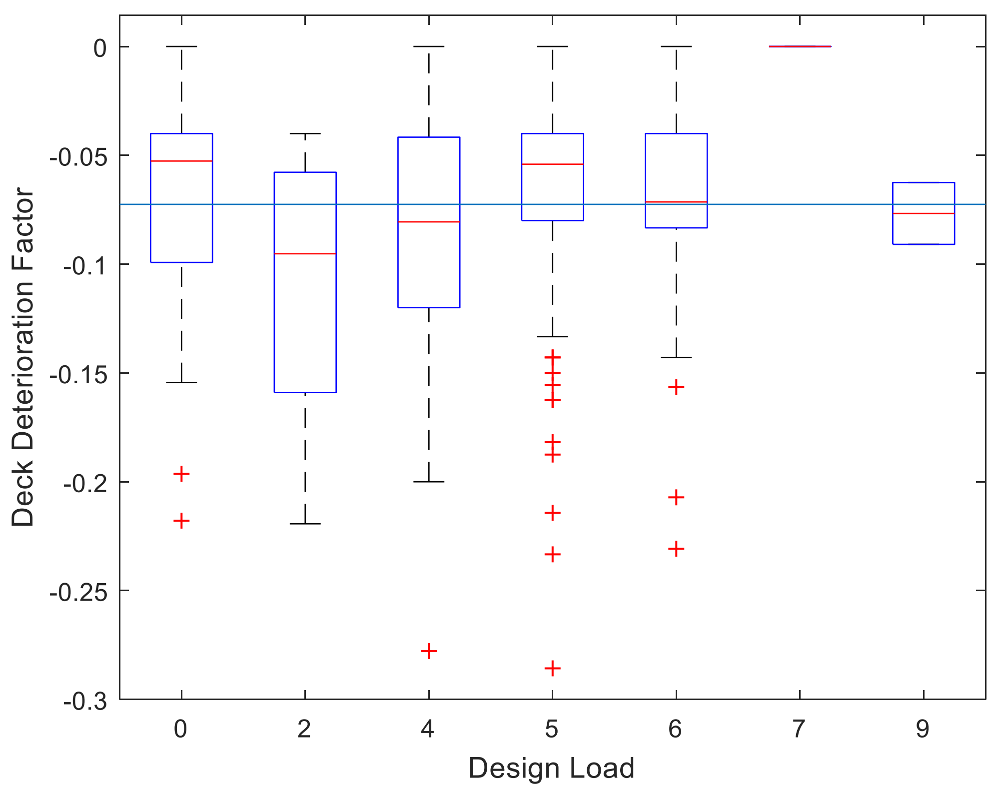


Figure 13: Box plot for Deck Deterioration Factor vs. Design Load

The Box plot for Deck Deterioration Factor vs. Type of Service has also a rating of 0 which stands for other and makes it impossible to judge its influence on the deterioration factor. Category 1 stands for highways. In Figure 13, it was observed that the deterioration rates for higher loads are not necessarily higher than for smaller loads. In the figure unterhalb, highways (category 1) have a mean deterioration factor smaller than the overall average. Railroads, covered by category 2, have a higher deterioration rate than highways. The reason for this should be investigated by analyzing the ADT on the two types to see if there is any correlation. Categories 6, 7 and 8 describe different levels of structures in interchanges, the majority of bridges of that type have smaller deterioration factors than the overall average is.

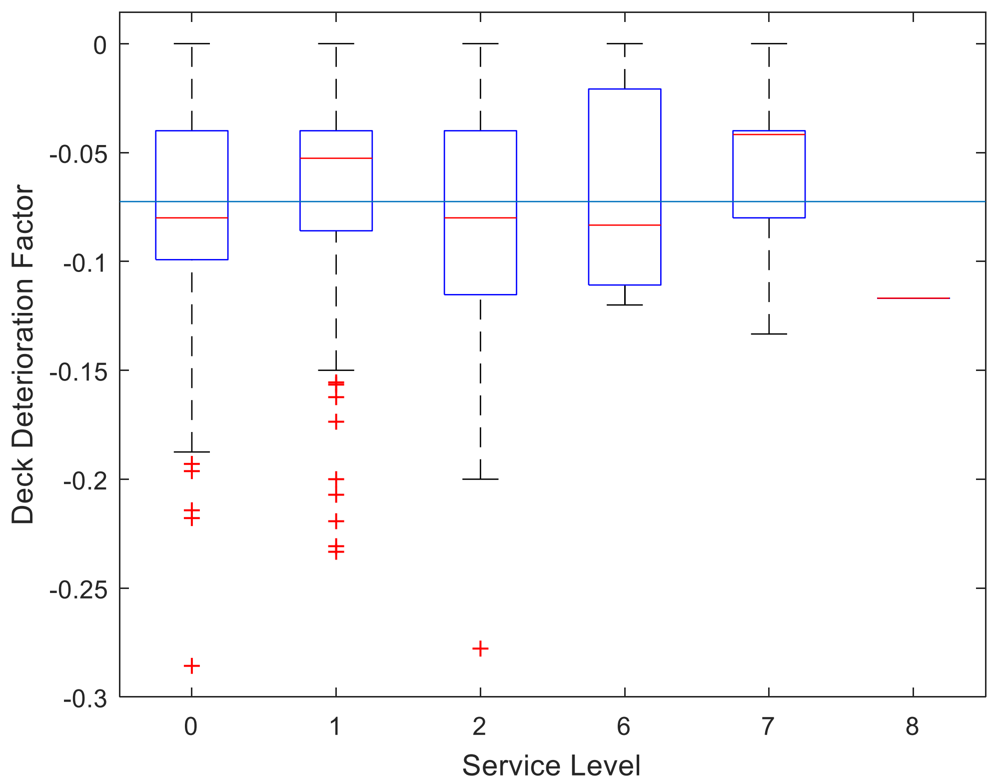


Figure 14: Box plot for Deck Deterioration Factor vs. Type of service on bridge

Shown in Figure 15 is the location analysis for the bridge deck deterioration factors. A color scale is used to present the different deterioration rates. The scale reaches from red (highest deterioration rates) to blue (smallest deterioration rates). Grey dots stand for neglected bridges. This figure shows what Figure 10 already showed in a different way: the majority of bridges have a deterioration factor below -0.1. What also can be observed is, that most of the bridges are situated along major highways (I95 and I295). It is also evident, that most of the bridges with higher deterioration rates are situated along those highways.

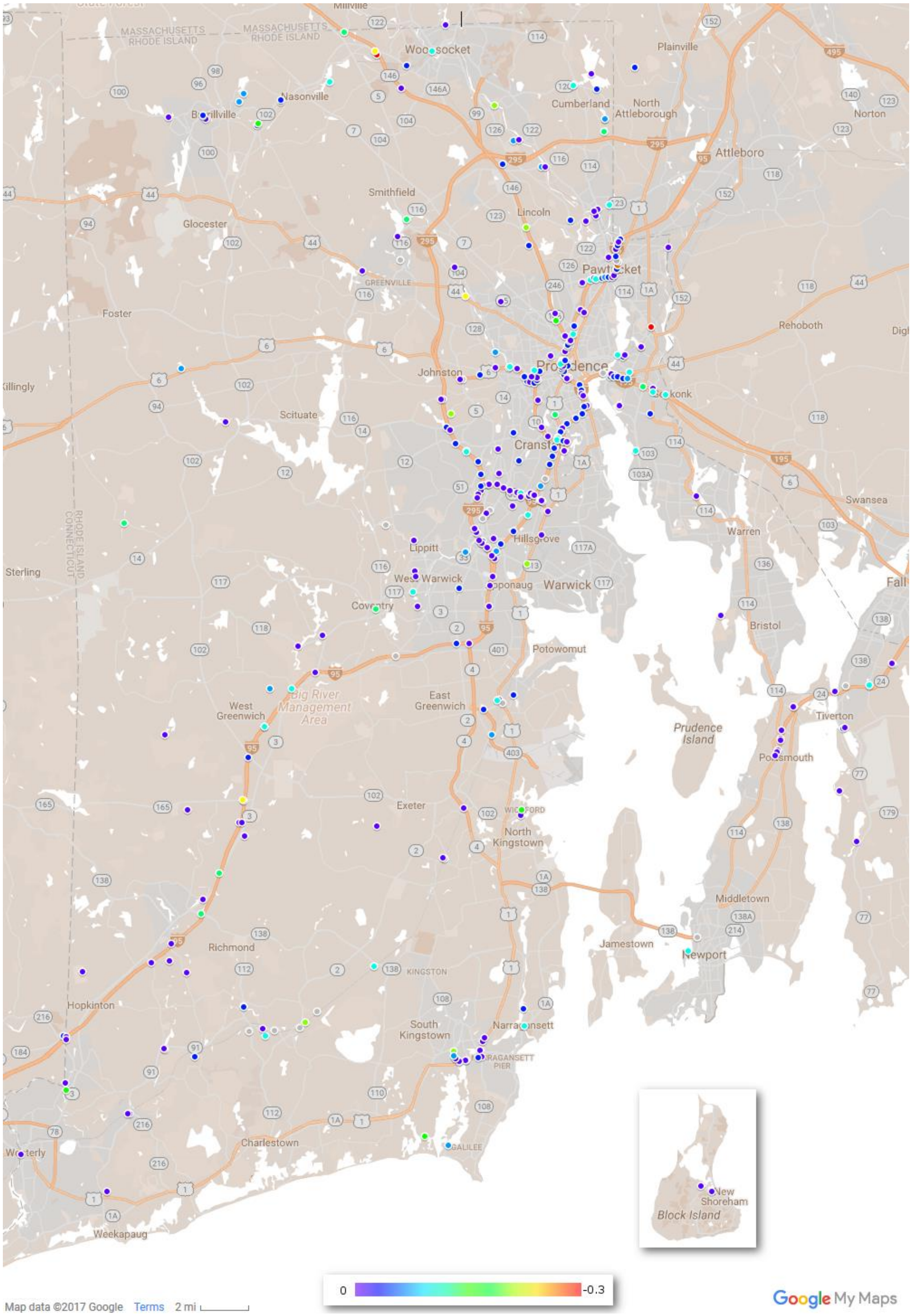


Figure 15: Location analysis for deck deterioration factors

Correlations to time-variant parameter

In this category fewer parameter were under investigation. All parameters are shown in scatter graphs below, as well as the computed correlation factors in Table 6. To not be misleading: the deterioration factor of each bridge is defined as constant, no updating of it is considered. Therefore, the bridge deck rating is considered as the reference factor in this section.

As it can be observed in Table 6, the correlation between ADT and bridge deck rating is similar to the correlation between ADTT and bridge deck rating. Therefore, just one curve fitting is shown (Figure 16) here. Both curve fittings can be viewed in Appendix G. With an R-square value of 0.000726 the correlation cannot be classified as existent.

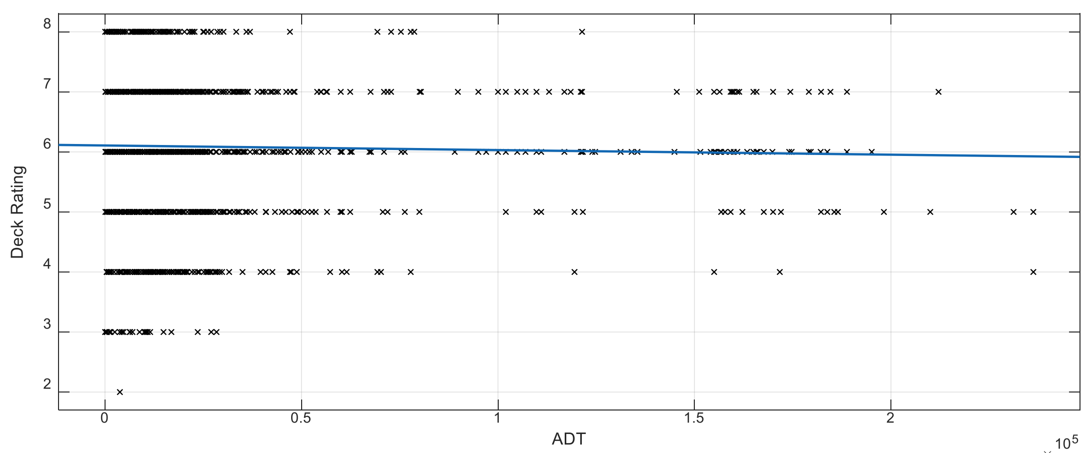


Figure 16: Correlation between bridge deck rating and ADT

Table 6: Correlation Factors for bridge deck rating to time-variant parameters

Parameter	R-square	R-square adjusted
ADT	0.000726	0.00060
ADTT	0.000673	0.00055
Superstructure Rating	0.315143	0.31506
Substructure Rating	0.232951	0.23286

The correlation between deck rating and superstructure rating is the strongest correlation which was found for this section of the study – although an R-square of 0.3151 is not a really strong correlation. For the figure unterhalb, lots of data-points are overlapping. Therefore, histograms were plotted next to the scatter graph in the Appendix.

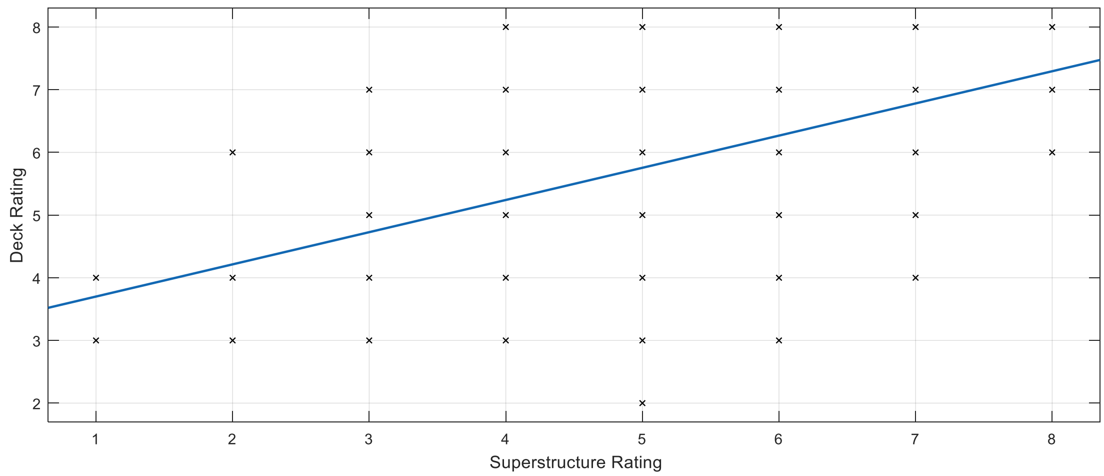


Figure 17: Correlation between bridge deck rating and superstructure rating

3.2.2. Superstructure

Average Deterioration Factor

The split of the superstructure deterioration factor is shown in Figure 18. It is similar to the histogram for the bridge deck deterioration factors. The majority of bridges have a deterioration factor between -0.03 and -0.12 (243 bridges, 73.64%). Just 11 bridges (3.33%) have a deterioration factor of 0. The remaining 23 % (76 bridges) are in a range between -0.12 and -0.34. The highest deterioration factor for the superstructure is -0.34 which is higher than the highest deterioration factor for the bridge deck. Due to too many changes of the rating from one year to another, 17 bridges had to be neglected. The average superstructure deterioration factor is -0.0934.

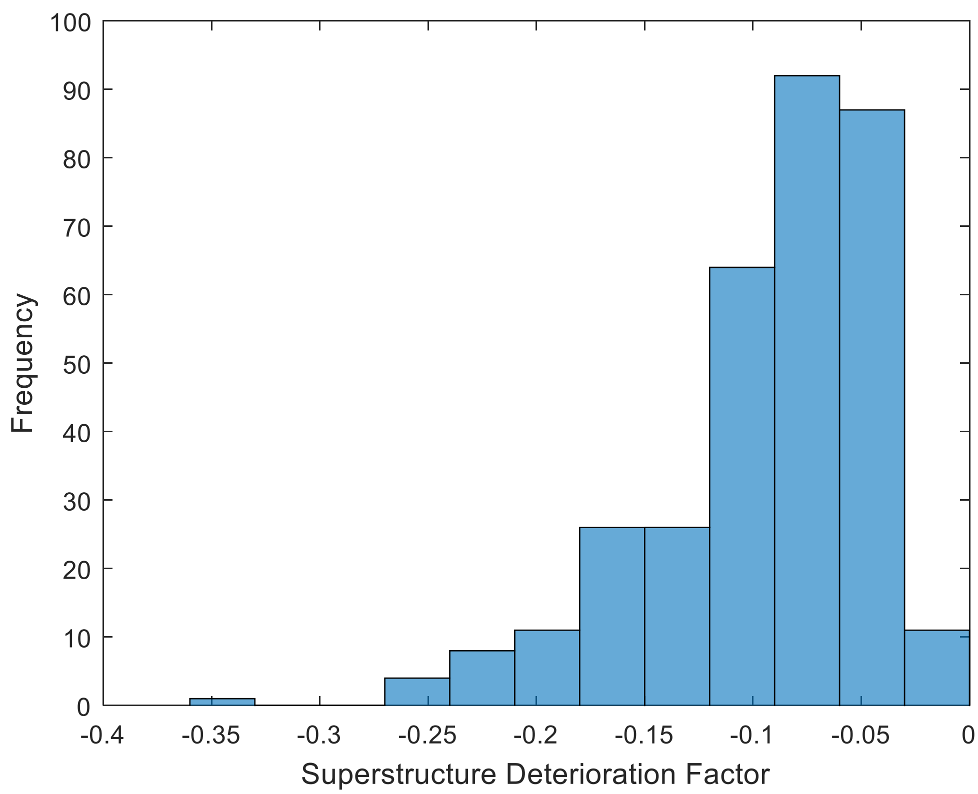


Figure 18: Deterioration rates superstructure

Correlations to time-invariant parameters

The analysis of the time-invariant parameter for the superstructure showed that there are no correlations. The highest R-square value was computed for the correlation between superstructure deterioration factor and year built with 0.00722 (see Table 7 for all values). That value is even smaller than the computed R-square for the bridge deck deterioration factor to year built (0.04483). Since this correlation is that weak, no graph is plotted here, although the produced graphs can be found in Appendix H.

Table 7: Correlation Factors for superstructure deterioration to non-discrete time-invariant parameters

Parameter	R-square	R-square adjusted
Span length	0.001831	-0.00121
Structure length	0.000811	-0.00224
Year built	0.007220	0.004193

The following box plots show the spread of the superstructure deterioration factor versus traffic lanes on structure, design load and type of service. Those were also shown for the bridge deck analysis. For the superstructure also the main building material (kind of material, item 43A), as well as the type of the design (item 43B) are of interest and therefore shown in Figure 23 and Figure 22. The blue line shows the average superstructure deterioration factor of -0.0934.

Figure 19 shows the superstructure deterioration factor vs traffic lanes on the structure. Observed in Figure 12, the deterioration rates for uneven numbers of traffic lanes on the structure were higher than for even numbers. This hypothesis cannot be supported by the observation of the superstructure deterioration rates in Figure 19. The highest rates can be observed for 2 and 4 lanes on the structure, with some outliers for 3 lanes on the structure.

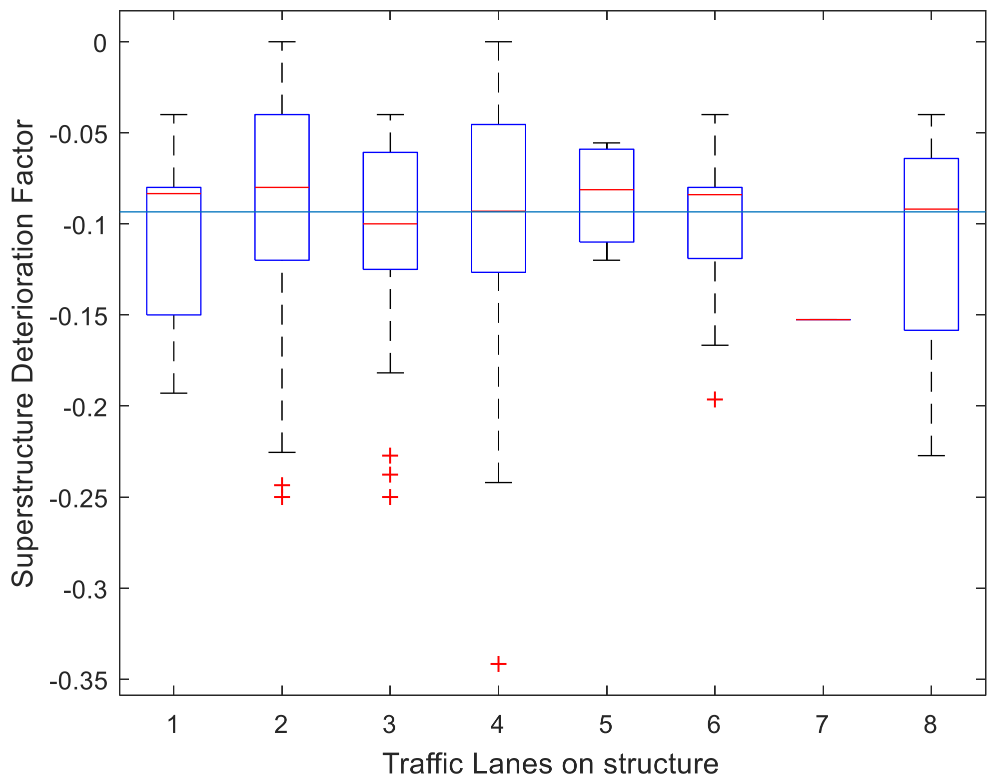


Figure 19: Box plot for Superstructure Deterioration Factor vs. Traffic Lanes on structure

An interpretation for deterioration factors in the design load category 0 (Other or unknown loads) in Figure 20 cannot be made. Categories 2, 4, 5 and 6 show very similar values. The mean of each category is approximately -0.08 and their 75th percentile is between -0.19 and -0.23. Categories 4, 5 and 6 show outliers up to -0.25, whereas category 5 even has one outlier at -0.34. Since those values are all very close, a new hypothesis why they are as they are cannot be stated.

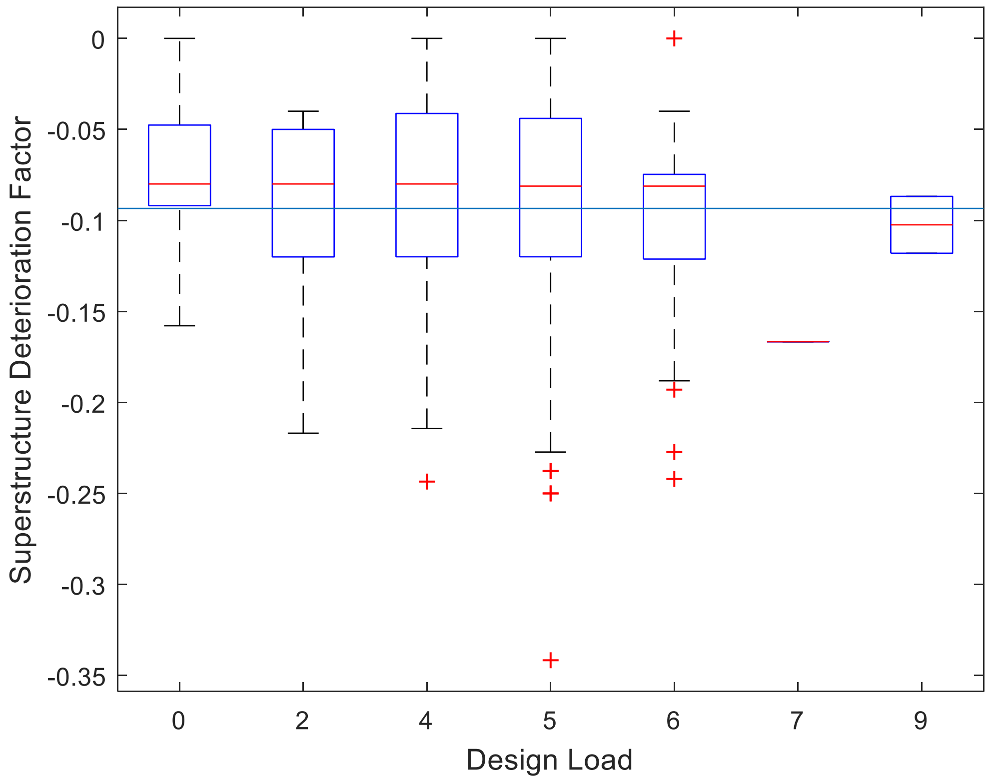


Figure 20: Box plot for Superstructure Deterioration Factor vs. Design load

Remarkable for Figure 21 are the high superstructure deterioration factors for category 6 (overpass structures or second level of a multilevel interchange). This is quite interesting since for the bridge deck analysis of this item, the investigation showed that category 1 and 2 (highway and railroad) showed the highest values.

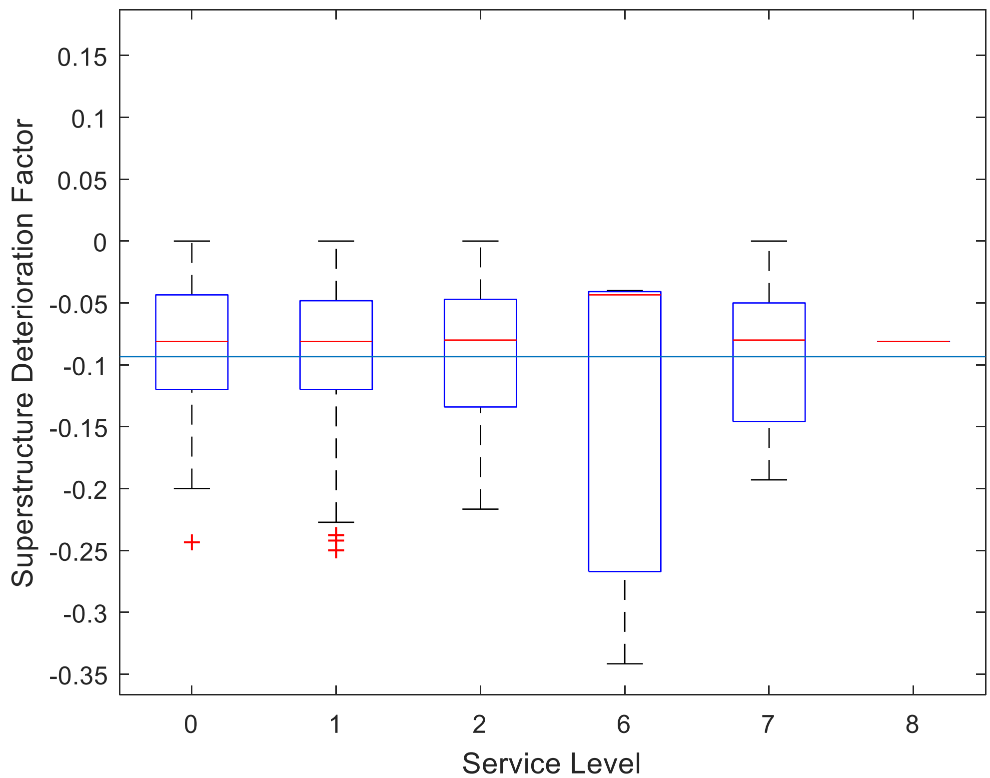


Figure 21: Box plot for Superstructure Deterioration Factor vs. Type of service

The box plot unterhalb shows the spread of the superstructure deterioration factor over different materials. Like for all other plots, category 0 refers to other kinds of materials, so it cannot be interpreted. The highest deterioration factors can be found within categories 3 (steel) and 5 (prestressed concrete). Other categories – category 1 (concrete), 2 (concrete continuous), 4 (steel continuous) and 7 (wood or timber) show maximum deterioration factors between -0.13 and -0.17 (with the exception of two outliers in category 2 and 4). The reasons for the peaks in steel and prestressed concrete bridges should be investigated.

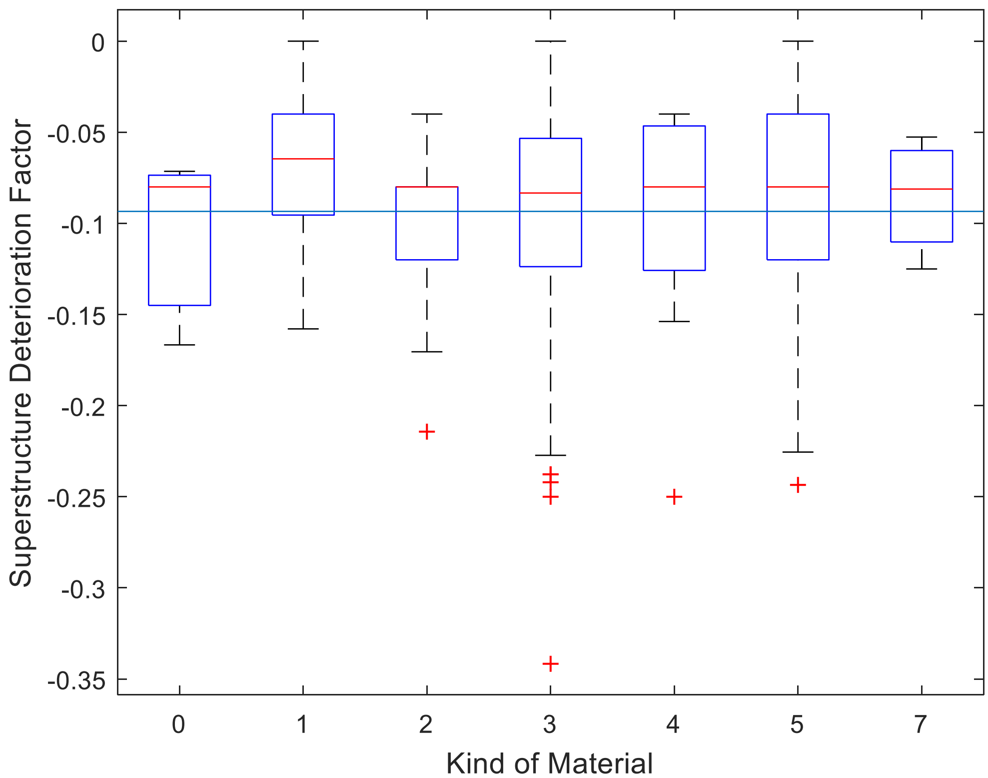


Figure 22: Box plot for Superstructure Deterioration Factor vs. Kind of Material

In Figure 23 the type of design is evaluated. Category 0 cannot be interpreted since all non-classified structure types are summarized under this category. Highest superstructure deterioration factors can be found within the categories 2 (Stringer/Multi-beam or Girder) and 5 (Box Beam or Girders – Multiple), followed by categories 4 (Tee Beam) and 1 (Slab). Why exactly those categories have higher deterioration rates should be investigated in further research.

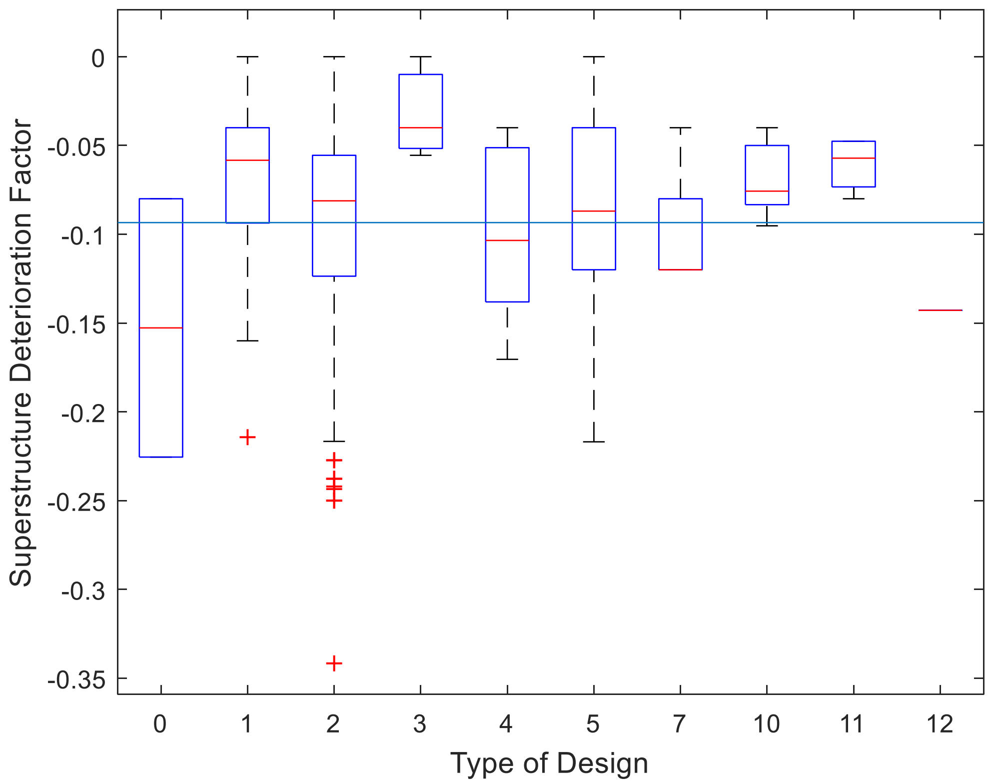


Figure 23: Box plot for Superstructure Deterioration Factor vs. Type of Design

The in Figure 24 shown map differs from the one in Figure 15 on the first sign: there are more light blue markers than dark blue ones. This was expected due to observations done in Figure 10 compared to Figure 18 (histograms of the deterioration rates of bridge deck and superstructure). It can also be observed, that higher deterioration rates are not only limited to bridges along bigger highways, they also can be found on less important routes. Thus, the bridges with the highest deterioration rates can be found along I95.

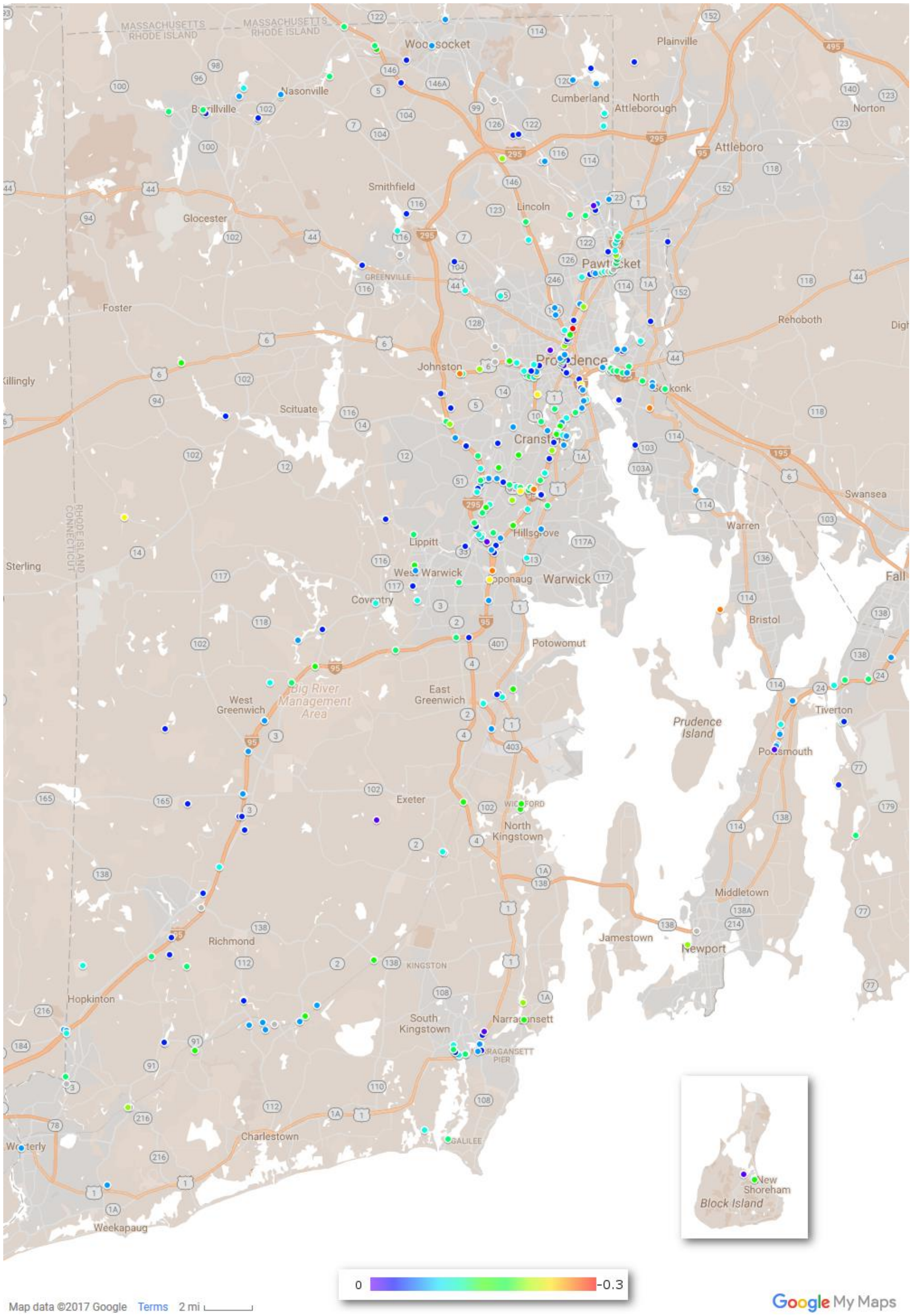


Figure 24: Location analysis for superstructure deterioration factors

Correlations to time-variant parameter

In this section the superstructure rating is considered as the reference factor, since the superstructure deterioration factor is time-invariant.

The observed correlations between the superstructure rating and other time-variant parameter are similar to the computed values of the bridge deck. Correlation to ADT and ADTT are similar to each other, however not strong at all. Therefore no scatter plot is shown here (it can be found in Appendix H).

Also similar to the bridge deck investigation are the correlations to other condition ratings. The correlation to the deck rating is slightly higher than to the substructure but can still not considered to be strong. Due to the high similarities graphs for those correlations are also not shown at this place, they can be found in Appendix H. Table 8 lists all computed correlation factors.

Table 8: Correlation Factors for superstructure rating to time-variant parameters

Parameter	R-square	R-square adjusted
ADT	0.002253	0.002132
ADTT	0.001894	0.001773
Deck Rating	0.305483	0.305399
Substructure Rating	0.258478	0.258388

3.2.3. Substructure

Average Deterioration Factor

The split of the superstructure deterioration factor is shown in Figure 32. It is a little different to the histograms for the bridge deck and superstructure deterioration factors. 21 bridges (6.46%) have a deterioration factor of 0. In the range between -0.02 and - 0.04 are the most bridges (74 bridges, 22.78%). The range between -0.04 and -0.06 is, in comprehension to bridge deck and superstructure an outlier. Only 34 bridges (10.46%) are in this category. Another big part, 108 bridges (33.23%), is settled in the range between -0.06 and -0.10. The remaining split of the bridges is very similar to bridge deck and superstructure, it spreads from -0.1 to -0.26 (88 bridges, 27.07%). The highest deterioration factor for the substructure is -0.244, which is the lowest maximum deterioration factor overall. Due to too many changes of the rating from one year to another, 22 bridges had to be neglected. The average substructure deterioration factor is -0.08048.

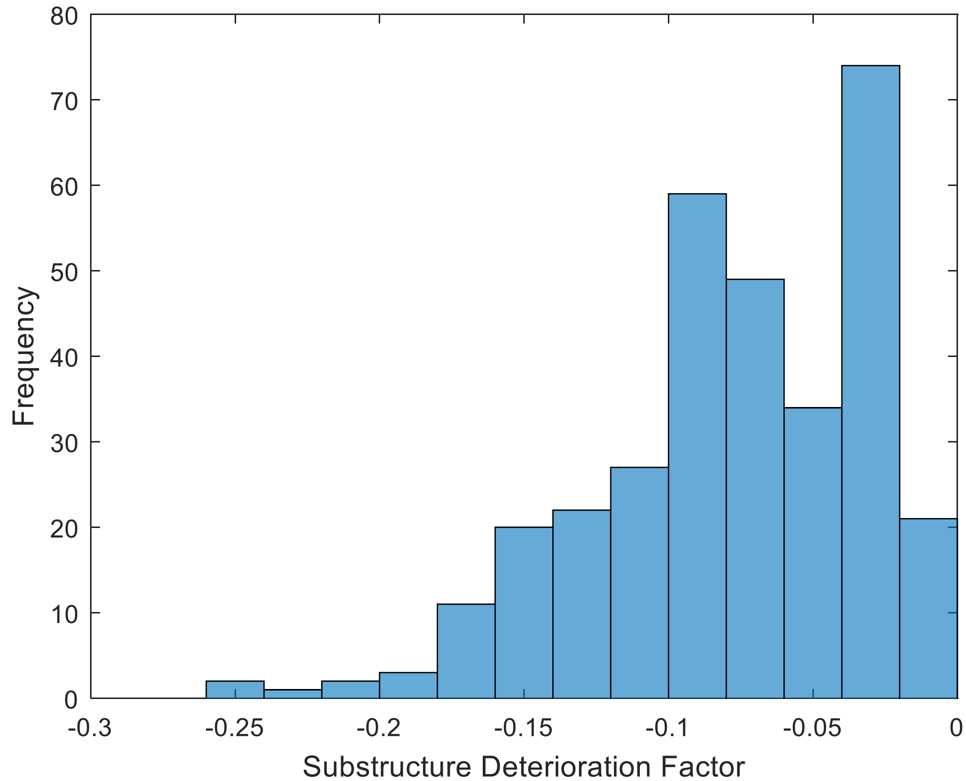


Figure 25: Deterioration factors substructure

Correlations to time-invariant parameters

Contrary to expectations, the correlation factor for substructure deterioration factor vs. year built is not the highest factor. The highest correlation factor was computed for the correlation between substructure deterioration factor and structure length. Although this result was unexpected, it is not showing a strong relation which can be used for better predictions. The remaining correlation factors can be found in Table 9. Since all correlations are non-representative, no graphs are plotted here (graphs can be found in Appendix I).

Table 9: Correlation Factors for substructure deterioration to non-discrete time-invariant parameters

Parameter	R-square	R-square adjusted
Span length	0.002161	-0.000928
Structure length	0.025296	0.022278
Year built	0.016467	0.013422

The following box plots show the spread of the substructure deterioration factor versus traffic lanes on structure, design load, type of service, main building material and type of the design. The blue line shows the average substructure deterioration factor of -0.08048.

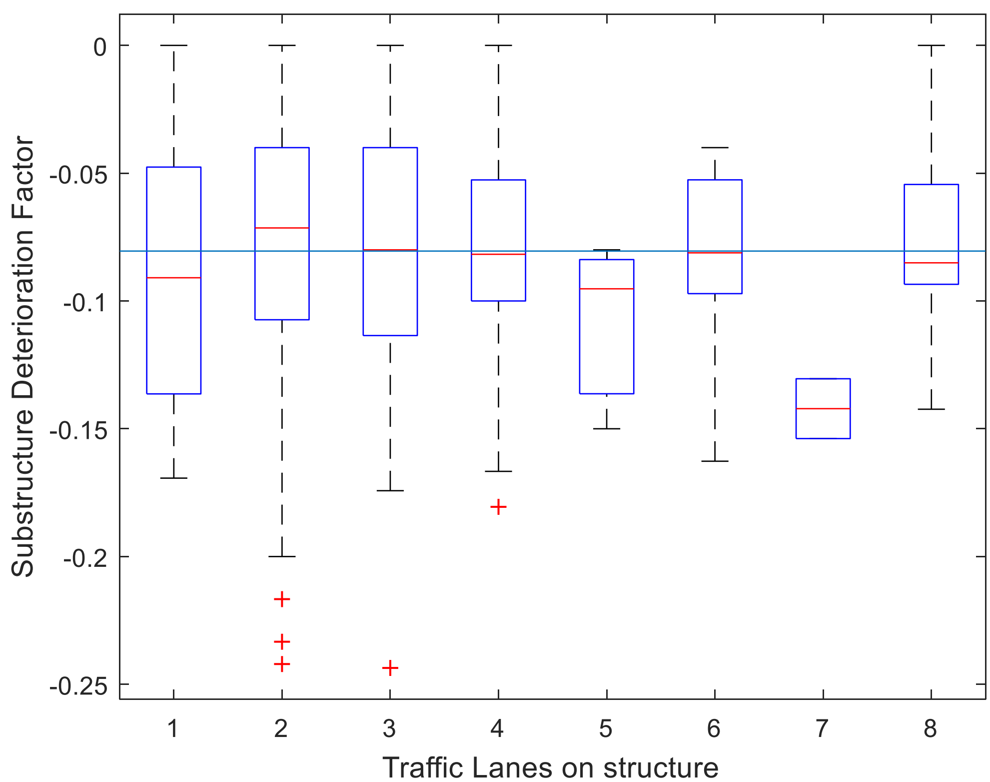


Figure 26: Box plot for Substructure Deterioration Factor vs. Traffic Lanes on structure

Figure 26 shows the substructure deterioration factor vs traffic lanes on the structure. The in 3.2.1 stated hypothesis, that uneven number of lanes on the structure could cause higher deterioration rates can also not be supported through observations for the substructure. Highest deterioration rates can be found for 2 or 3 lanes on the structure.

The spread of substructure deterioration factors over the design load, as shown in Figure 27, is relatively even over categories 2 and 5 – their mean deterioration factors are close to the overall average deterioration factor and the highest deterioration factors are approximately -0.2 and -0.21. Just one outliner is existent in category 5.

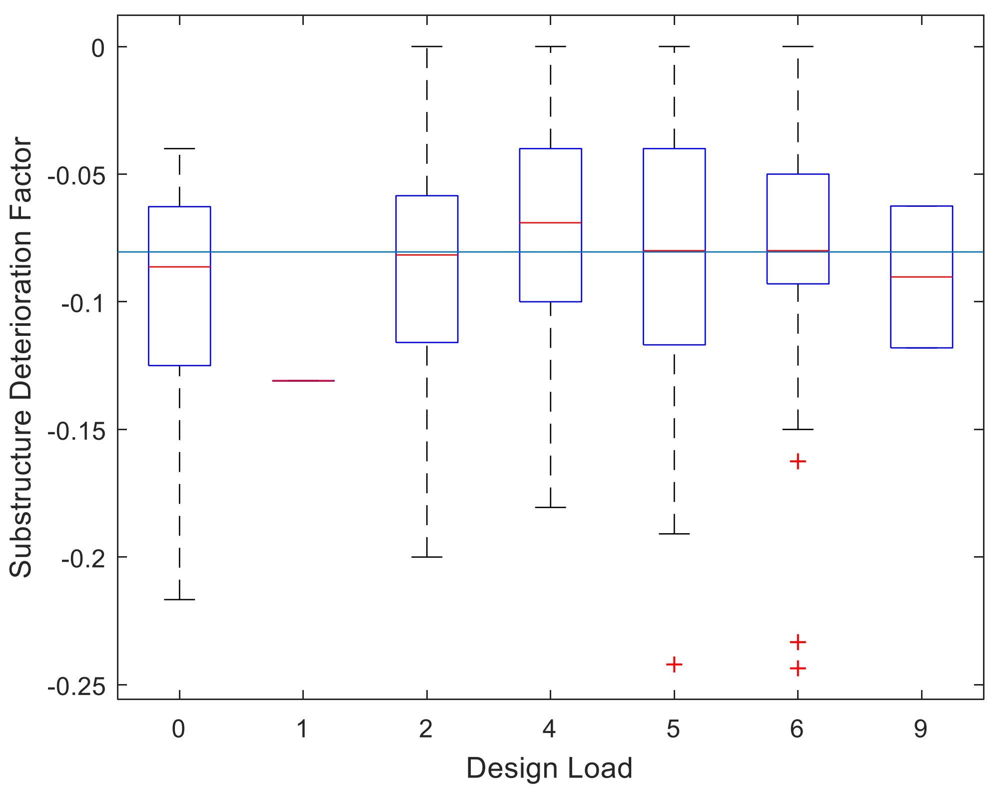


Figure 27: Box plot for Substructure Deterioration Factor vs. Design load

In Figure 28, it can be observed, that the highest substructure deterioration factors are within categories 1 (highway) and 2 (railroad). This trend is unexpected, since it was observed for bridge deck deterioration factors, but not for the superstructure deterioration factors and therefore considered as an exception. Further research should be done to investigate the reasons for it.

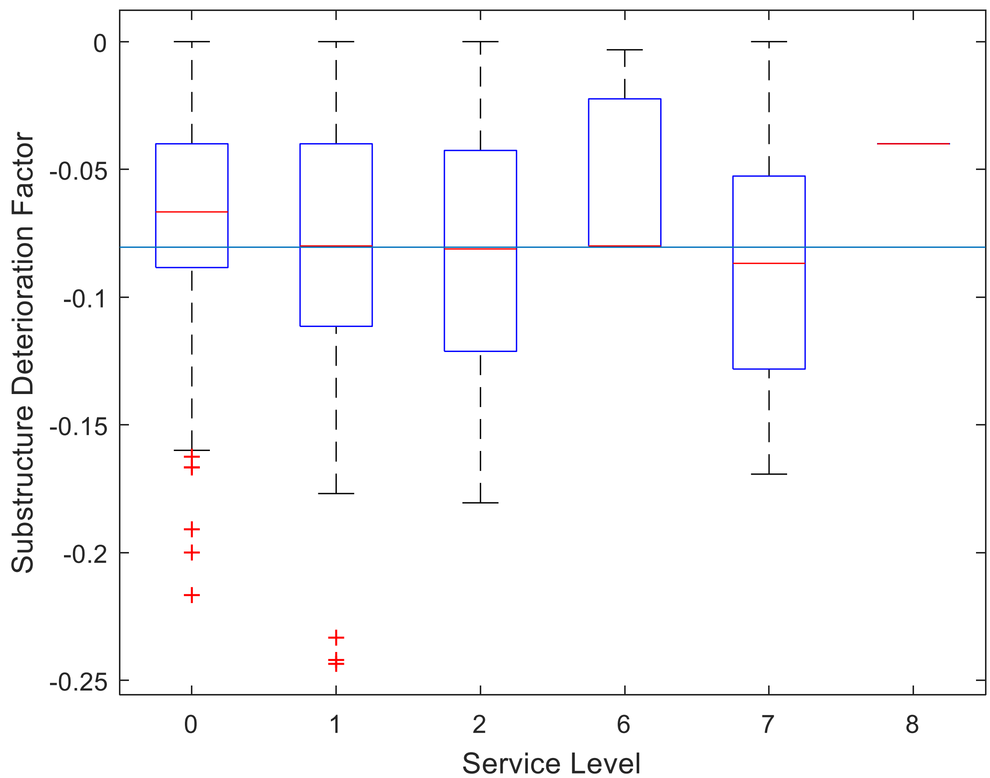


Figure 28: Box plot for Substructure Deterioration Factor vs. Type of service

In the box plot below the spread of the substructure deterioration factor over different materials is shown. The highest deterioration factors can be found within categories 3 (steel) and 7 (wood or timber). Category 5 (prestressed concrete) has substructure deterioration factors up to -0.19 and has therefore the third highest deterioration factors. Categories 1 (concrete), 2 (concrete continuous) and 4 (steel continuous) show maximum deterioration factors between -0.14 and -0.17 (with the exception of one outlier in 4). This result is similar to those obtained from bridge deck and superstructure investigations, although bridges of category 5 (prestressed concrete) show a high variation.

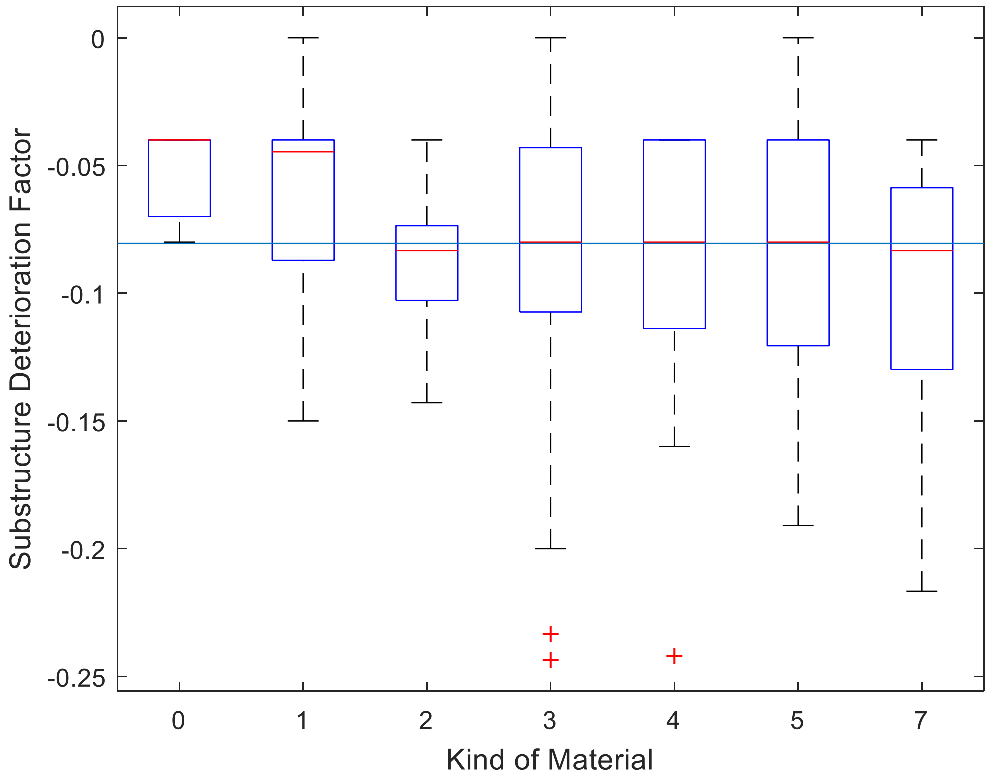


Figure 29: Box plot for Substructure Deterioration Factor vs. Kind of Material

In Figure 30 the design type is evaluated. By far, the highest superstructure deterioration factors can be found within category 2 (Stringer/Multi-beam or Girder). It is followed by categories 1 (slab), 4 (tee beam), and 5 (box beam or girders – multiple) with substructure deterioration factors up to -0.15. To have the maximum deterioration factors within category 2 is also the case for bridge deck and superstructure investigation which could be a trend worth to investigate in future work.

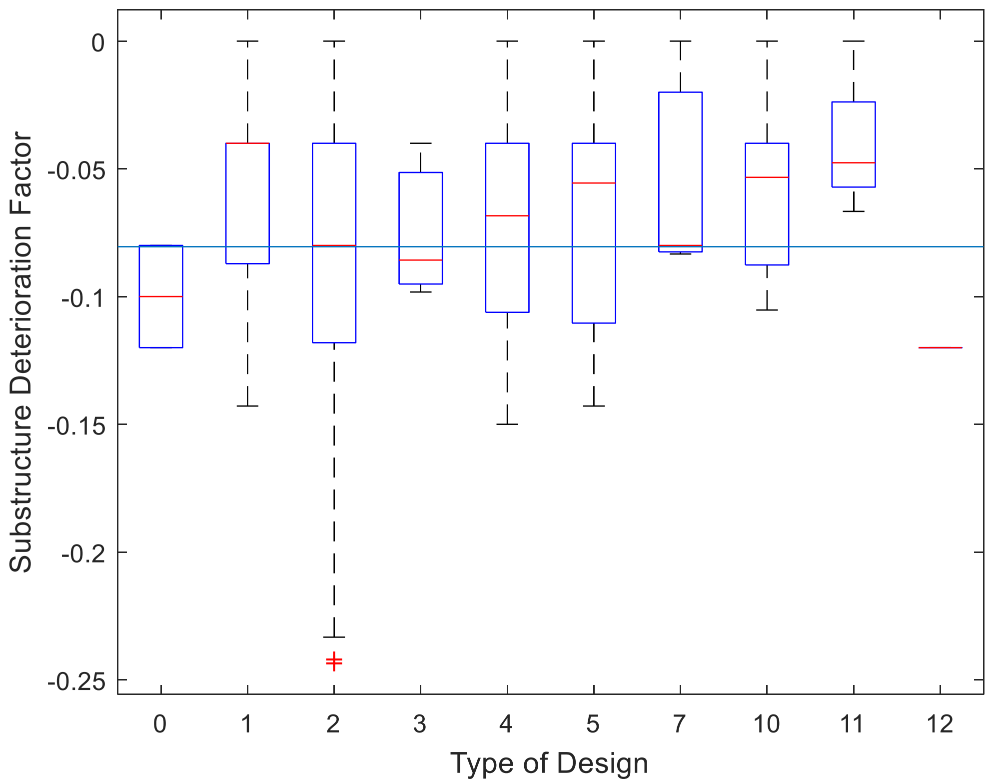


Figure 30: Box plot for Substructure Deterioration Factor vs. Type of Design

The in Figure 31 shown map displays the substructure deterioration factors. It is remarkable, that the generated map for substructure is similar to the map for superstructure, but differs to the map for the bridge deck deterioration factors. For example, deterioration factors around the area of Pawtucket (I95) are higher for superstructure and substructure than for the bridge deck. What Figure 28 already showed, is also visible in the map: the highest deterioration factors can be found on a railroad between Providence and Westerly. Other high deterioration factors can be found along highways as expected. It can also be observed that around Burriville higher substructure deterioration factors are present.

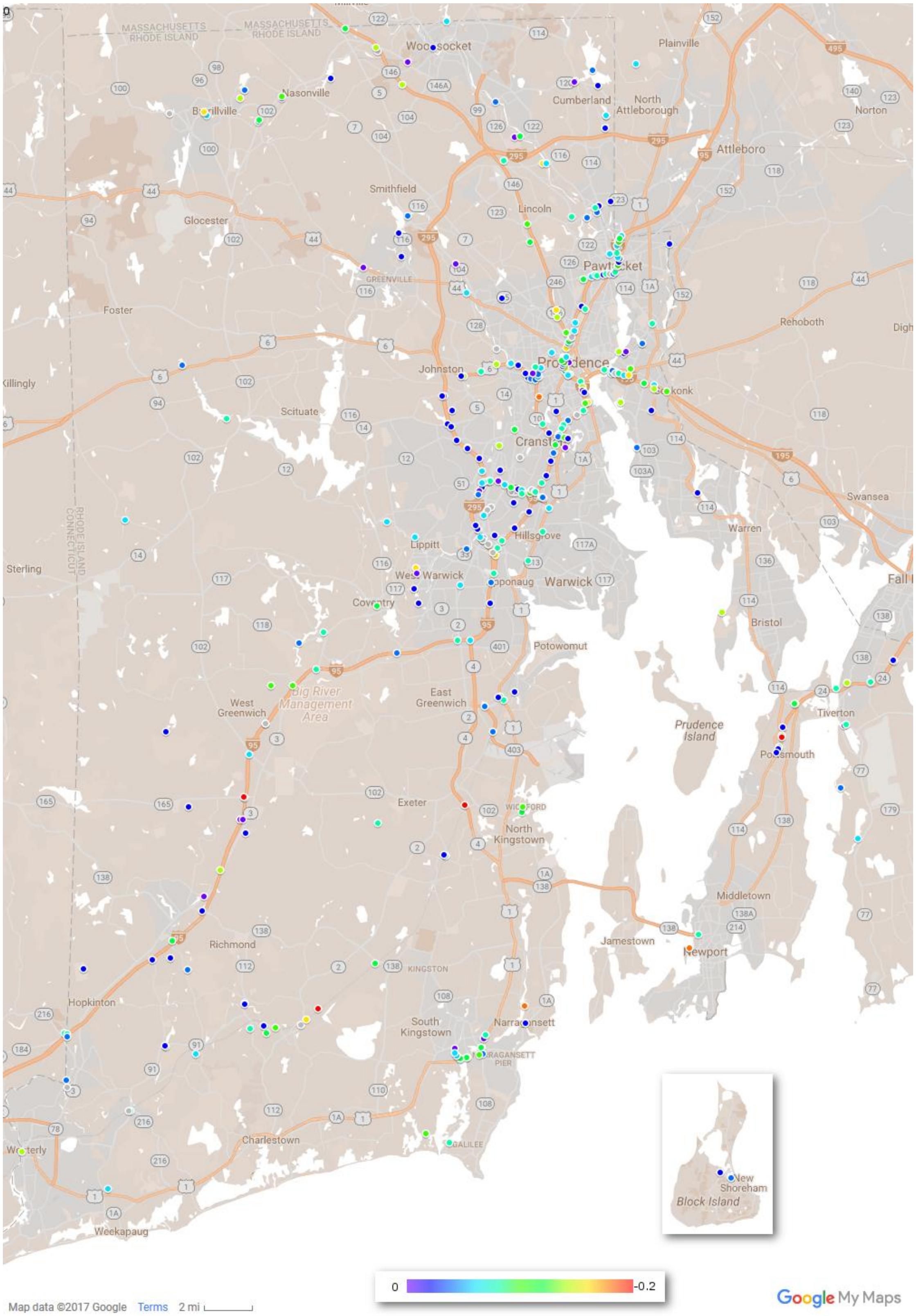


Figure 31: Location analysis for substructure deterioration factors

Correlations to time-variant parameter

In this section the substructure rating is considered as the reference factor, since the substructure deterioration factor is time-invariant.

The observed correlations between the substructure rating and other time-variant parameter are similar to the computed values of the bridge deck and superstructure. Correlations to ADT and ADTT are similar to each other, however not strong at all. Therefore no scatter plot is shown here (it can be found in Appendix I).

Also, similar to the bridge deck investigation are the correlations to other condition ratings. The correlation to the superstructure rating is slightly higher than to the deck rating but can still not considered to be strong. Due to the high similarities, graphs for those correlations are also not shown at this place, they can be found in Appendix I as well. Table 10 lists all computed correlation factors.

Table 10: Correlation Factors for substructure rating to time-variant parameters

Parameter	R-square	R-square adjusted
ADT	0.00165728	0.001534361
ADTT	0.00165299	0.001530068
Deck Rating	0.2368903	0.236796351
Superstructure Rating	0.26856949	0.268479444

3.3. Deterioration Model

Following the process described in 2.3.1, three transition probability matrices were developed. Each for bridge deck, superstructure and substructure, which are shown in Table 11 through Table 13. Like expected, it can be observed that all transition probability matrices have a similar form. Most values are settled around the diagonal of the matrix. Since maintenance is taken into account during the computations, it is possible that values under the diagonal appear. The first and last column – ratings 9 and 0 – are filled with zeros. That is an expected behavior. However, those columns were not left out in order to use them as a form of check value to assure no invalid data was used for computation. Another check value is the sum of each row: it has to be equal to 1 [8].

In general, ratings are most likely to be constant between two inspections. Ratings between 8 and 6 are more likely to decrease than increase, whereas ratings below 6 are more likely to increase due to maintenance. The transition probability matrix for bridge deck and substructure both include the factor one for once. For the bridge deck this factor has its origin in two transitions and for the substructure in one transition. Therefore, those factors should not be taken as representatives.

Table 11: Transition probability matrix bridge deck

	9	8	7	6	5	4	3	2	1	0
9	0	**1.000**	0	0	0	0	0	0	0	0
8	0	**0.623**	**0.312**	**0.050**	**0.008**	**0.008**	0	0	0	0
7	0	**0.009**	**0.823**	**0.157**	**0.011**	0.001	0	0	0	0
6	**0.001**	**0.007**	**0.033**	**0.873**	**0.072**	**0.011**	**0.002**	0	0	0
5	0	**0.019**	**0.042**	**0.045**	**0.822**	**0.068**	**0.003**	0	0	0
4	0	**0.074**	**0.037**	**0.037**	**0.050**	**0.758**	**0.044**	0	0	0
3	0	**0.196**	**0.043**	**0.022**	**0.043**	**0.109**	**0.522**	**0.065**	0	0
2	0	0	0	0	0	0	0	**1.000**	0	0
1	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0

Table 12: Transition probability matrix superstructure

	9	8	7	6	5	4	3	2	1	0
9	**0.667**	**0.333**	0	0	0	0	0	0	0	0
8	0	**0.577**	**0.372**	**0.045**	0	0	**0.006**	0	0	0
7	0	**0.008**	**0.743**	**0.208**	**0.031**	**0.010**	0	0	0	0
6	0	**0.003**	**0.026**	**0.818**	**0.132**	**0.020**	**0.001**	0	0	0
5	**0.001**	**0.008**	**0.021**	**0.051**	**0.825**	**0.083**	**0.008**	**0.002**	0	0
4	0	**0.035**	**0.041**	**0.026**	**0.100**	**0.753**	**0.046**	0	0	0
3	0	**0.088**	**0.059**	**0.010**	**0.029**	**0.098**	**0.686**	**0.020**	**0.010**	0
2	0	0	0	**0.500**	0	0	0	**0.500**	0	0
1	0	**0.400**	0	0	0	0	0	0	**0.600**	0
0	0	0	0	0	0	0	0	0	0	0

Table 13: Transition probability matrix substructure

	9	8	7	6	5	4	3	2	1	0
9	**0.667**	0	**0.333**	0	0	0	0	0	0	0
8	0	**0.531**	**0.420**	**0.049**	0	0	0	0	0	0
7	0	**0.011**	**0.705**	**0.251**	**0.031**	**0.003**	0	0	0	0
6	**0.001**	**0.002**	**0.034**	**0.845**	**0.108**	**0.010**	**0.001**	0	0	0
5	0	**0.003**	**0.029**	**0.069**	**0.813**	**0.082**	**0.002**	0	**0.001**	0
4	0	**0.029**	**0.041**	**0.059**	**0.079**	**0.760**	**0.033**	0	0	0
3	0	**0.033**	**0.033**	**0.033**	**0.017**	**0.100**	**0.767**	**0.017**	0	0
2	0	0	0	0	0	0	0	**1.000**	0	0
1	0	0	0	0	0	**1.000**	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0

Overall, 2290 transitions have been evaluated. Most transitions have been performed from an initial rating of 6, closely followed by initial ratings of 7 and 5. On average, 800 transitions have happened from 6 as an initial rating, 596 transitions have happened from 7 as an initial rating and 515 have happened from 5 as an initial rating. Those initial ratings are the majority, which makes them the most reliable transition probabilities.

Using equation (2), a prediction for future conditions can be made. On the basis of the just stated observations, predictions are done for initial ratings of 5, 6 and 7 for one, five, ten, twenty-five and fifty years [8].

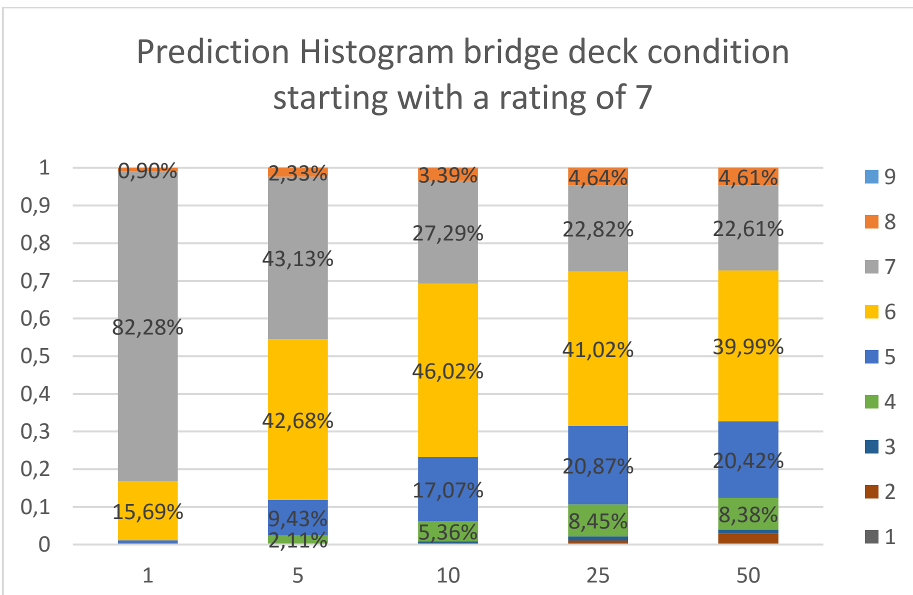


Figure 32: Prediction Histogram for bridge deck condition

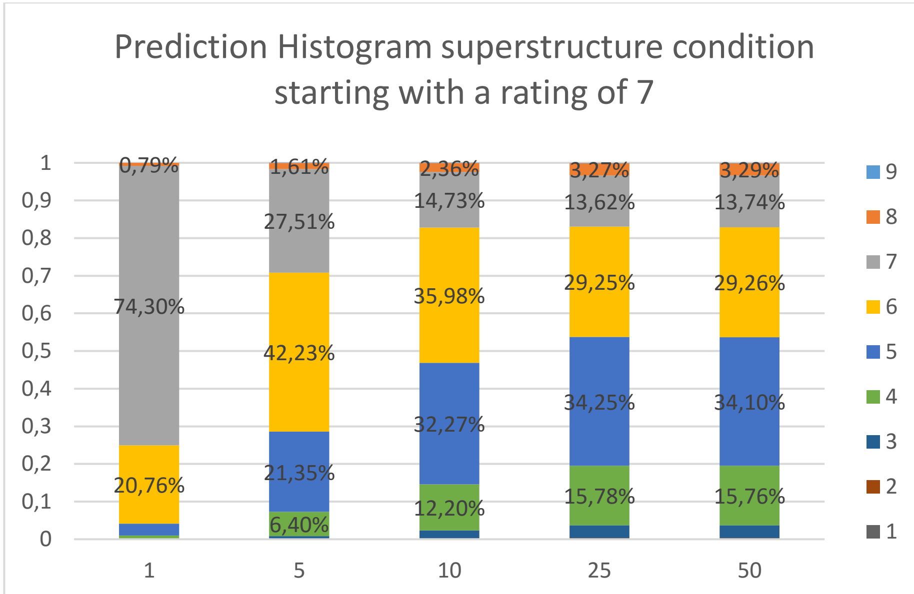


Figure 33: Prediction Histogram for superstructure condition

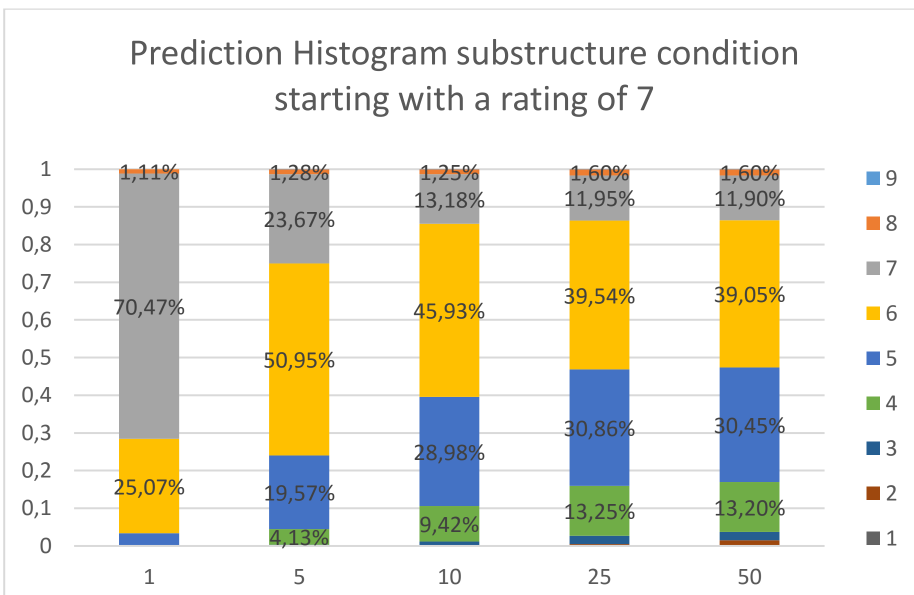


Figure 34: Prediction Histogram for substructure condition

CHAPTER 4

4. CONCLUSIONS

4.1. Summary

In this study, a Markov Chain based deterioration Model has been developed. After a brief description of Bridge Management in the US, bridge condition ratings are discussed in detail. Then, the approach for developing a deterioration model is discussed.

Chapter 2 shows how the process of developing a deterioration model was done. First, the verification of the data was ensured by sorting out inconsistent datasets. The second step is described in section 2.2 – deterioration factors, transition probabilities and correlation factors were computed. But, even though inconsistent datasets were already sorted out, the data had to be checked again for their condition ratings – just ratings which didn't show too much fluctuation were considered to compute deterioration factors. After choosing those items, correlations were calculated with a curve fitting toolbox in MatLab.

Listed in chapter 3 are the gained results of this study. The first part states how many datasets had to be sorted out and for which reasons. Several examples are given for different types of inconsistent datasets. The second part of chapter 3 describes the computed correlations between the investigated items. It is split up into three parts – the condition rating of bridge deck, superstructure and substructure. In those parts the correlations are described by following a schema: it starts off with the evaluation of the deterioration factor itself, followed by correlations for time-invariant parameters including the location analysis, and correlations for time-variant parameters. The third part of chapter 3 describes and analyses the results of developing the deterioration model.

4.2. Results and future work

During filtering the available datasets, more than 60% of the data had to be neglected due to various reasons. This decreases the credibility of the deterioration model and leaves room for further investigations why so much data is having errors. To compensate for time periods with missing data, special techniques could be used to simulate data. That could lead to more valid data and therefor to more credibility. Additionally to simulate data, original inspection reports should be requested which might makes real condition ratings available which have not been submitted to the Federal Highway Administration (FHWA).

The computation of correlation between deterioration factors and time-invariant parameters, as well as computations of correlations between condition ratings and time-variant parameters did not bring strong correlations to daylight. This is an expected behavior, since it was also observed in previous studies [8]. Newly developed in this present study were maps for deterioration factors. The calculated deterioration factors for superstructure were the highest followed by deterioration factors for substructure and bridge deck where most of the higher deterioration factors were situated in similar areas for each category. The maps could be investigated in depth by varying the shown data. It is believed, and data can support this belief, that the most promising approach for further investigations regarding deterioration is the average daily traffic (ADT).

The developed deterioration model is capable of estimating the likelihood for future conditions of bridges regarding bridge deck, superstructure and substructure. Although the amount of data is limiting the credibility of the model, a sufficient amount of transitions with initial conditions of 5, 6 and 7 have been observed. That makes predictions for those initial conditions the most accurate within the developed model and is even usable as a tool to estimate future conditions in limited boundaries. Future work should include the Bayesian Network approach for the development of a deterioration model. It is expected that, once implemented correctly, the Bayesian Network could use even weak correlations for computing reliable future conditions for single bridges. The implementation of the Bayesian Network should therefore include more research regarding correlations factors between deterioration and different parameters like average daily traffic, structure kind or lanes on structure.

Appendices

Appendix A. Structure Inventory and Appraisal Sheet

Appendix A

OMB No. 2125-0501

Structure Inventory and Appraisal Sheet

NATIONAL BRIDGE INVENTORY - - - - - - - STRUCTURE INVENTORY AND APPRAISAL 10/15/94

```
********** IDENTIFICATION **********************
(1) STATE NAME - ____________          CODE ___
(8) STRUCTURE NUMBER                  #_______________
(5) INVENTORY ROUTE (ON/UNDER) - ____ = ________
(2) HIGHWAY AGENCY DISTRICT                        __
(3) COUNTY CODE  ___   (4) PLACE CODE          _____
(6) FEATURES INTERSECTED - ____________________
(7) FACILITY CARRIED     - ______________
(9) LOCATION             - ____________________
(11) MILEPOINT/KILOMETERPOINT                  ___.___
(12) BASE HIGHWAY NETWORK - _________ CODE     _
(13) LRS INVENTORY ROUTE & SUBROUTE    #__________
(16) LATITUDE          __ DEG __ MIN __.__ SEC
(17) LONGITUDE         __ DEG __ MIN __.__ SEC
(98) BORDER BRIDGE STATE CODE ___ % SHARE __ %
(99) BORDER BRIDGE STRUCTURE NO.  #_____________

********** STRUCTURE TYPE AND MATERIAL *********
(43) STRUCTURE TYPE MAIN:  MATERIAL - __________
       TYPE - _______________          CODE ___
(44) STRUCTURE TYPE APPR:  MATERIAL - __________
       TYPE - _______________          CODE ___
(45) NUMBER OF SPANS IN MAIN UNIT              ___
(46) NUMBER OF APPROACH SPANS                  ____
(107) DECK STRUCTURE TYPE - ____________ CODE _
(108) WEARING SURFACE / PROTECTIVE SYSTEM:
  A) TYPE OF WEARING SURFACE - __________ CODE _
  B) TYPE OF MEMBRANE        - __________ CODE _
  C) TYPE OF DECK PROTECTION - __________ CODE _

********** AGE AND SERVICE *********************
(27) YEAR BUILT                                ____
(106) YEAR RECONSTRUCTED                       ____
(42) TYPE OF SERVICE:  ON - ____________________
         UNDER - ________________       CODE __
(28) LANES:  ON STRUCTURE __  UNDER STRUCTURE __
(29) AVERAGE DAILY TRAFFIC                   ______
(30) YEAR OF ADT  ___   (109) TRUCK ADT      __ %
(19) BYPASS, DETOUR LENGTH                  ___ KM

********** GEOMETRIC DATA **********************
(48) LENGTH OF MAXIMUM SPAN                ____._ M
(49) STRUCTURE LENGTH                     ______._ M
(50) CURB OR SIDEWALK:   LEFT __._ M  RIGHT __._ M
(51) BRIDGE ROADWAY WIDTH CURB TO CURB      ___._ M
(52) DECK WIDTH OUT TO OUT                  ___._ M
(32) APPROACH ROADWAY WIDTH (W/SHOULDERS)   ___._ M
(33) BRIDGE MEDIAN - _______________ CODE  _
(34) SKEW   __ DEG   (35) STRUCTURE FLARED   _
(10) INVENTORY ROUTE MIN VERT CLEAR         __.__ M
(47) INVENTORY ROUTE TOTAL HORIZ CLEAR      ___._ M
(53) MIN VERT CLEAR OVER BRIDGE RDWY        __.__ M
(54) MIN VERT UNDERCLEAR    REF - _____  __.__ M
(55) MIN LAT UNDERCLEAR RT  REF - _____  __._ M
(56) MIN LAT UNDERCLEAR LT                  __._ M

********** NAVIGATION DATA *********************
(38) NAVIGATION CONTROL - ____________ CODE _
(111) PIER PROTECTION   - ____________ CODE _
(39) NAVIGATION VERTICAL CLEARANCE          ___._ M
(116) VERT-LIFT BRIDGE NAV MIN VERT CLEAR   ___._ M
(40) NAVIGATION HORIZONTAL CLEARANCE       ____._ M

************************************************

SUFFICIENCY RATING = ___._
STATUS = ________________

********** CLASSIFICATION ***************** CODE
(112) NBIS BRIDGE LENGTH -                    __
(104) HIGHWAY SYSTEM       - _______________  __
(26) FUNCTIONAL CLASS      - _______________  __
(100) DEFENSE HIGHWAY      - _______________  _
(101) PARALLEL STRUCTURE   - _______________  _
(102) DIRECTION OF TRAFFIC - _______________  _
(103) TEMPORARY STRUCTURE  - _______________  _
(105) FEDERAL LANDS HIGHWAYS - _____________  _
(110) DESIGNATED NATIONAL NETWORK - ________  _
(20) TOLL                  - _______________  _
(21) MAINTAIN              - _______________  __
(22) OWNER                 - _______________  __
(37) HISTORICAL SIGNIFICANCE - _____________  _

********** CONDITION ********************** CODE
(58) DECK                                       _
(59) SUPERSTRUCTURE                             _
(60) SUBSTRUCTURE                               _
(61) CHANNEL & CHANNEL PROTECTION               _
(62) CULVERTS                                   _

********** LOAD RATING AND POSTING ******** CODE
(31) DESIGN LOAD       - ________ OR ________  _
(63) OPERATING RATING METHOD - _____________   _
(64) OPERATING RATING -        ________       __._
(65) INVENTORY RATING METHOD - _____________   _
(66) INVENTORY RATING -        ________       __._
(70) BRIDGE POSTING    - _______________       _
(41) STRUCTURE OPEN, POSTED OR CLOSED -        _
     DESCRIPTION - _________________________

********** APPRAISAL ********************** CODE
(67) STRUCTURAL EVALUATION                      _
(68) DECK GEOMETRY                              _
(69) UNDERCLEARANCES, VERTICAL & HORIZONTAL     _
(71) WATERWAY ADEQUACY                          _
(72) APPROACH ROADWAY ALIGNMENT                 _
(36) TRAFFIC SAFETY FEATURES                  ____
(113) SCOUR CRITICAL BRIDGES                    _

********** PROPOSED IMPROVEMENTS ***************
(75) TYPE OF WORK - _______________    CODE ___
(76) LENGTH OF STRUCTURE IMPROVEMENT     ______._ M
(94) BRIDGE IMPROVEMENT COST          $___,___,000
(95) ROADWAY IMPROVEMENT COST         $___,___,000
(96) TOTAL PROJECT COST               $___,___,000
(97) YEAR OF IMPROVEMENT COST ESTIMATE       ____
(114) FUTURE ADT                           ______
(115) YEAR OF FUTURE ADT                     ____

********** INSPECTIONS *************************
(90) INSPECTION DATE __/__  (91) FREQUENCY  __ MO
(92) CRITICAL FEATURE INSPECTION:     (93) CFI DATE
  A) FRACTURE CRIT DETAIL - __ - __ MO  A)  __/__
  B) UNDERWATER INSP      - __ - __ MO  B)  __/__
  C) OTHER SPECIAL INSP   - __ - __ MO  C)  __/__
```

Source: [7]

Appendix B. Listing of approved bridges after sorting

20, 60, 70, 110, 140, 150, 170, 200, 220, 230, 260, 300, 480, 500, 520, 550, 560, 570, 580, 610, 780, 1010, 1070, 1120, 1170, 1180, 1260, 1310, 1350, 1390, 1400, 1450, 1490, 1510, 1550, 1590, 1630, 1640, 1790, 1820, 1850, 1930, 1940, 1970, 2040, 2480, 2490, 2500, 2570, 2600, 2610, 2670, 2700, 2740, 2750, 2760, 2780, 2840, 2860, 2870, 2910, 2920, 2940, 2990, 3010, 3020, 3070, 3080, 3100, 3260, 3270, 3340, 3350, 3400, 3480, 3540, 3550, 3570, 3590, 3630, 3650, 3680, 3690, 3700, 3710, 3720, 3730, 3780, 3820, 3890, 3950, 3960, 4020, 4040, 4060, 4070, 4080, 4140, 4160, 4170, 4210, 4220, 4230, 4240, 4250, 4280, 4290, 4300, 4310, 4420, 4460, 4470, 4490, 4510, 4530, 4540, 4560, 4570, 4580, 4590, 4600, 4620, 4630, 4640, 4650, 4660, 4670, 4680, 4690, 4700, 4710, 4720, 4730, 4760, 4770, 4780, 4790, 4800, 4810, 4812, 4820, 4830, 4840, 4842, 4850, 4852, 4860, 4862, 4870, 4880, 4890, 4900, 4910, 4930, 4940, 4990, 5000, 5010, 5040, 5050, 5060, 5070, 5080, 5090, 5110, 5130, 5140, 5180, 5190, 5200, 5370, 5390, 5420, 5440, 5450, 5460, 5480, 5490, 5500, 5520, 5530, 5540, 5550, 5560, 5570, 5580, 5590, 5600, 5610, 5612, 5620, 5622, 5630, 5632, 5650, 5660, 5670, 5680, 5690, 5692, 5710, 5720, 5730, 5740, 5750, 5760, 5770, 5780, 5790, 5800, 5810, 5820, 5830, 5840, 5850, 5860, 5862, 5880, 5882, 5890, 5900, 5910, 5912, 5920, 5922, 5930, 5940, 5950, 5960, 5970, 6000, 6020, 6040, 6050, 6060, 6070, 6090, 6110, 6112, 6160, 6180, 6190, 6200, 6210, 6220, 6230, 6240, 6250, 6260, 6270, 6280, 6290, 6300, 6310, 6320, 6330, 6340, 6350, 6360, 6370, 6380, 6390, 6420, 6422, 6440, 6450, 6452, 6460, 6462, 6470, 6480, 6490, 6492, 6500, 6502, 6510, 6520, 6540, 6550, 6560, 6570, 6580, 6590, 6600, 6620, 6630, 6640, 6650, 6660, 6670, 6680, 6700, 6710, 6720, 6730, 6740, 6750, 6760, 6770, 6780, 6800, 6810, 6820, 6830, 6840, 6850, 6860, 6890, 6920, 6970, 7000, 7010, 7020, 7030, 7040, 7050, 7070, 7080, 7090, 7120, 7130, 7140, 7190, 7200, 7210, 7212, 7220, 7222, 7230, 7240, 7250, 7252, 7260, 7270, 7272, 7280, 7282, 7290, 7292, 7300, 7302, 7310, 7320, 7322, 7340, 7342

Appendix C. Listing of removed bridges

Removed because of 0-rating

650, 3970, 4010, 5400, 6940, 6980, 7350, 7352, 7362, 7370, 7372, 7400, 7402, 7410, 7420, 7422, 7430, 7432, 7450, 7452, 7460, 7462, 7470, 7480, 7482, 7490, 7500, 7502, 7510, 7520, 7522, 7530, 7532, 7540, 7550, 7552, 7570, 7572, 7600, 7610, 7630, 7660, 7670, 7680, 7690, 7700, 7710, 7720, 7730, 7740, 7750, 7760, 7770, 7780, 7790, 7800, 7810, 7820, 7830, 7840, 7850, 7860, 7870, 7880, 7890, 7900, 7910, 7960, 7970, 7980, 8000, 8200, 8210, 8220, 8230, 8240, 8270, 8280, 8290, 8300, 8310, 8320, 8330, 8340, 8360, 8370, 8380, 8390, 8400, 8410, 8412, 8420, 8440, 8450, 8460, 8480, 8520, 8530, 8540, 8550, 8560, 8580, 8590, 8600, 8610, 8630, 8640, 8650, 8652, 8660, 8670, 8672, 8680, 8690, 8700, 8710, 8720, 8730, 8740, 8750, 8760, 8770, 8780, 8790, 8800, 8820, 8830, 8840, 8870, 8880, 8900, 8910, 8930, 8940, 8950, 8960, 8980, 8990, 9000, 9020, 9022, 9030, 9040, 9050, 9060, 9070, 9080, 9140, 9150, 9160, 9170, 9180, 9190, 9200, 9210, 9220, 9230, 9240, 9250, 9260, 9270, 9280, 9290, 9300, 9310, 9320, 9330, 9340, 9350, 9360, 9370, 9380, 9390, 9400, 9410, 9430, 9440, 9450, 9460, 9500, 9510, 9520, 9530, 9550, 9560, 9570, 9590, 9600, 9630, 9670, 9700, 9720, 9730, 9740, 9750, 9770, 9780, 9790, 9800, 9810, 9812, 9820, 9830, 9840, 9842, 9850, 9860, 9870, 9880, 9890, 9900, 9910, 9920, 9930, 9960, 9970, 10010, 10020, 10030, 10040, 10050, 10060, 10070, 10080, 10090, 10100, 10110, 10120, 10130, 10140, 10230, 10240, 10270, 10280, 10310, 10370, 10420, 10430, 10440, 10450, 10470, 10620, 10700, 10710, 10720, 10730, 10740, 10750, 10760, 10770, 10780, 10790, 10800, 10810, 10820, 10830, 10970, 11780, 11980, 15510

Removed because of structure is a culvert

10, 250, 270, 280, 320, 340, 350, 360, 370, 380, 410, 430, 440, 450, 460, 490, 540, 640, 710, 770, 810, 840, 930, 950, 1000, 1050, 1060, 1080, 1083, 1110, 1200, 1210, 1230, 1240, 1340, 1440, 1460, 1480, 1500, 1580, 1740, 1780, 1870, 1900, 1950, 1960, 1980, 1990, 2010, 2060, 2080, 2130, 2190, 2220, 2240, 2270, 2420, 2450, 2460, 2560, 2630, 2640, 2690, 2710, 2730, 2762, 2790, 2950, 2960, 3050, 3150, 3230, 3280, 3370, 3440, 3470, 3502, 3530, 3560, 3750, 3760, 3770, 3830, 3840, 3910, 4030, 4050, 4120, 4130, 4180, 4190, 4270, 4330, 4400, 4410, 4412, 4430, 4450, 4480, 4550, 4750, 4950, 4970, 5120, 5150, 5160, 5170, 5470, 5640, 6430, 6530, 6870, 6880, 6910, 7100, 7920, 7930, 7940, 7950, 8470, 8810, 8850, 8860, 8890, 9090, 9100, 9110, 9120, 9262, 9420, 9470, 9480, 9490, 9492, 9540, 9580, 9582, 9592, 9640, 9650, 9660, 9662, 9680, 9690, 9760, 9940, 9950

Removed because of missing condition ratings

180, 240, 630, 1290, 1620, 1880, 2430, 2930, 3170, 3880, 3900, 4200, 4320, 4350, 4390, 5210, 5220, 5230, 5240, 5250, 5260, 5270, 5280, 5290, 5300, 5310, 5320, 5330, 5340, 5350, 5360, 5430, 6010, 6080, 6610, 6990, 7060, 7150, 7160, 7170, 7180, 7440, 7560, 7580, 7640, 7650, 8030, 8060, 8070, 8080, 8110, 8140, 8142, 8150, 8160, 8190, 8430, 8920, 9610, 9620, 9980, 10250, 10260, 10920, 10980, 10990, 11410, 11660, 11990, 12160, 12240, 12290, 12300, 12360, 12440, 12470, 12480, 1RI0668, 1RI0669, 1RI1366, 1RI1400, 1RIGTE2

Removed because of inconsistent inspection intervals

590, 1370, 2000, 2880, 3000, 3030, 3040, 3060, 3062, 3500, 3510, 3670, 4000, 4340, 4440, 4500, 5020, 5100, 5380, 6030, 6690, 6790, 7360, 8490, 8500, 8510

Appendix D. Listing of Bridge IDs per evaluated category

Bridge Deck Rating

20, 60, 110, 140, 150, 170, 200, 220, 230, 260, 300, 480, 500, 520, 550, 560, 580, 610, 780, 1010, 1070, 1120, 1170, 1180, 1260, 1310, 1350, 1390, 1400, 1450, 1510, 1550, 1590, 1630, 1640, 1790, 1820, 1850, 1930, 1940, 1970, 2480, 2500, 2570, 2610, 2670, 2750, 2760, 2780, 2840, 2860, 2910, 2920, 2940, 2990, 3010, 3020, 3070, 3080, 3100, 3260, 3270, 3340, 3350, 3400, 3480, 3540, 3550, 3570, 3630, 3650, 3680, 3690, 3700, 3710, 3720, 3730, 3780, 3820, 3890, 3950, 3960, 4020, 4040, 4060, 4070, 4080, 4140, 4160, 4170, 4230, 4250, 4280, 4290, 4300, 4310, 4420, 4460, 4470, 4490, 4510, 4530, 4540, 4560, 4570, 4580, 4590, 4600, 4620, 4630, 4640, 4650, 4660, 4670, 4680, 4690, 4700, 4710, 4720, 4730, 4760, 4770, 4780, 4790, 4800, 4810, 4812, 4820, 4830, 4840, 4842, 4850, 4852, 4860, 4862, 4870, 4880, 4900, 4910, 4930, 4940, 4990, 5000, 5010, 5040, 5050, 5060, 5070, 5080, 5090, 5110, 5130, 5140, 5180, 5200, 5370, 5390, 5420, 5440, 5450, 5460, 5480, 5490, 5500, 5530, 5540, 5550, 5560, 5570, 5600, 5610, 5612, 5620, 5622, 5630, 5632, 5650, 5660, 5670, 5680, 5690, 5692, 5710, 5720, 5730, 5740, 5750, 5760, 5770, 5780, 5790, 5800, 5810, 5820, 5840, 5850, 5860, 5862, 5882, 5890, 5900, 5910, 5912, 5920, 5922, 5930, 5940, 5950, 5960, 5970, 6000, 6020, 6040, 6060, 6070, 6090, 6112, 6160, 6180, 6190, 6200, 6210, 6220, 6230, 6240, 6250, 6260, 6270, 6280, 6290, 6300, 6310, 6320, 6330, 6350, 6360, 6370, 6380, 6390, 6420, 6422, 6440, 6450, 6452, 6460, 6462, 6470, 6490, 6492, 6500, 6502, 6510, 6520, 6540, 6550, 6560, 6570, 6580, 6590, 6600, 6630, 6640, 6650, 6660, 6670, 6680, 6700, 6710, 6720, 6730, 6740, 6750, 6760, 6770, 6780, 6810, 6820, 6830, 6840, 6850, 6860, 6890, 6920, 6970, 7010, 7030, 7040, 7050, 7070, 7080, 7090, 7120, 7130, 7140, 7190, 7200, 7210, 7212, 7220, 7222, 7230, 7240, 7250, 7252, 7260, 7270, 7272, 7280, 7282, 7290, 7292, 7300, 7302, 7310, 7320, 7322, 7340, 7342

Superstructure Rating

20, 60, 70, 110, 140, 150, 170, 200, 220, 230, 260, 300, 480, 500, 550, 560, 570, 580, 610, 1010, 1070, 1120, 1170, 1180, 1260, 1310, 1350, 1390, 1400, 1450, 1510, 1550, 1590, 1630, 1640, 1820, 1850, 1930, 1940, 1970, 2040, 2480, 2500, 2570, 2600, 2610, 2670, 2700, 2740, 2750, 2760, 2780, 2840, 2860, 2910, 2920, 2940, 3010, 3020, 3070, 3080, 3100, 3260, 3270, 3340, 3350, 3400, 3480, 3540, 3550, 3570, 3630, 3650, 3680, 3690, 3700, 3710, 3720, 3730, 3780, 3820, 3890, 3950, 4020, 4040, 4060, 4070, 4080, 4140, 4160, 4170, 4210, 4220, 4230, 4240, 4250, 4280, 4290, 4300, 4310, 4420, 4460, 4470, 4490, 4510, 4530, 4540, 4560, 4580, 4590, 4600, 4620, 4630, 4640, 4660, 4670, 4680, 4690, 4700, 4710, 4720, 4730, 4760, 4770, 4780, 4790, 4800, 4810, 4812, 4820, 4830, 4840, 4842, 4850, 4852, 4860, 4862, 4870, 4880, 4890, 4900, 4910, 4930, 4940, 4990, 5000, 5010, 5040, 5050, 5060, 5070, 5080, 5090, 5110, 5130, 5140, 5180, 5190, 5200, 5370, 5390, 5420, 5440, 5450, 5460, 5480, 5490, 5520, 5530, 5550, 5560, 5570, 5580, 5590, 5600, 5610, 5612, 5620, 5622, 5630, 5632, 5650, 5660, 5670, 5680, 5690, 5692, 5720, 5730, 5740, 5750, 5760, 5770, 5780, 5790, 5800, 5810, 5820, 5830, 5840, 5850, 5860, 5862, 5882, 5890, 5900, 5910, 5912, 5920, 5922, 5930, 5940, 5950, 5960, 5970, 6000, 6020, 6040, 6050, 6060, 6090, 6110, 6112, 6160, 6180, 6190, 6200, 6210, 6220, 6230, 6240, 6250, 6260, 6270, 6280, 6290, 6300, 6310, 6320, 6330, 6340, 6350, 6360, 6370, 6380, 6390, 6420, 6422, 6440, 6450, 6452, 6460, 6462, 6470, 6480, 6490, 6492, 6500, 6502, 6510, 6520, 6540, 6550, 6560, 6570, 6580, 6590, 6600, 6620, 6630, 6640, 6650, 6660, 6670, 6680, 6700, 6710, 6720, 6730, 6740, 6750, 6760, 6770, 6780, 6800, 6810, 6820, 6830, 6840, 6850, 6860, 6890, 6920, 6970, 7000, 7010, 7020, 7030, 7040, 7050, 7070, 7080, 7090, 7120, 7130, 7140, 7190, 7200, 7210, 7212, 7220, 7222, 7230, 7240, 7252, 7260, 7270, 7272, 7280, 7282, 7290, 7292, 7300, 7302, 7310, 7320, 7322, 7340, 7342

Substructure Rating

20, 60, 70, 110, 140, 150, 170, 200, 220, 260, 300, 480, 500, 550, 560, 570, 580, 610, 1010, 1070, 1120, 1170, 1180, 1260, 1310, 1350, 1390, 1400, 1450, 1490, 1510, 1550, 1590, 1630, 1640, 1790, 1820, 1850, 1930, 1940, 1970, 2040, 2480, 2490, 2500, 2570, 2600, 2610, 2670, 2740, 2750, 2760, 2780, 2840, 2860, 2870, 2910, 2920, 2940, 2990, 3010, 3020, 3070, 3080, 3100, 3260, 3270, 3340, 3350, 3400, 3480, 3540, 3570, 3630, 3680, 3690, 3700, 3710, 3720, 3730, 3780, 3820, 3890, 3950, 3960, 4020, 4040, 4060, 4070, 4080, 4140, 4160, 4170, 4220, 4240, 4250, 4280, 4290, 4300, 4310, 4420, 4470, 4490, 4510, 4530, 4540, 4560, 4570, 4580, 4590, 4600, 4620, 4630, 4640, 4650, 4660, 4680, 4690, 4700, 4710, 4720, 4730, 4760, 4770, 4780, 4790, 4800, 4812, 4820, 4830, 4840, 4842, 4850, 4852, 4860, 4862, 4870, 4880, 4890, 4900, 4910, 4930, 4940, 4990, 5000, 5010, 5040, 5060, 5070, 5080, 5090, 5110, 5130, 5140, 5180, 5190, 5200, 5370, 5390, 5420, 5440, 5450, 5460, 5480, 5490, 5520, 5530, 5540, 5550, 5560, 5570, 5580, 5590, 5600, 5610, 5612, 5620, 5622, 5630, 5632, 5650, 5660, 5670, 5680, 5690, 5692, 5710, 5720, 5730, 5740, 5750, 5760, 5770, 5780, 5790, 5800, 5810, 5820, 5830, 5840, 5850, 5860, 5862, 5880, 5890, 5900, 5910, 5912, 5920, 5922, 5930, 5940, 5950, 5960, 5970, 6000, 6020, 6040, 6050, 6060, 6070, 6090, 6110, 6112, 6160, 6180, 6190, 6200, 6210, 6220, 6230, 6240, 6250, 6260, 6270, 6280, 6290, 6300, 6320, 6330, 6340, 6350, 6360, 6370, 6380, 6390, 6420, 6422, 6440, 6450, 6452, 6460, 6462, 6470, 6480, 6490, 6492, 6500, 6502, 6510, 6520, 6540, 6550, 6560, 6580, 6590, 6600, 6620, 6640, 6650, 6660, 6670, 6680, 6700, 6710, 6720, 6730, 6740, 6750, 6760, 6770, 6780, 6800, 6810, 6820, 6830, 6840, 6850, 6860, 6890, 6920, 6970, 7000, 7010, 7020, 7030, 7040, 7050, 7070, 7090, 7120, 7130, 7140, 7190, 7210, 7220, 7230, 7240, 7250, 7252, 7260, 7270, 7272, 7280, 7282, 7290, 7292, 7300, 7302, 7310, 7320, 7322, 7340, 7342

Appendix E. Time-variant and time-invariant parameters with description

Time-invariant parameters	Code	Description
#31 Design load	0-9	Use coding from 0-9 to describe live load Code / Metric Description / English Description 1 / M 9 / H 10 2 / M 13.5 / H 15 3 / MS 13.5 / HS 15 4 / M 18 / H 20 5 / MS 18 / HS 20 6 / MS18+Mod / HS 20+Mod 7 / Pedestrian / Pedestrian 8 / Railroad / Railroad 9 / MS 22.5 / HS 25 0 / Other or Unknown
#26 Functional classification	several	Code / Description Rural 01 Principal Arterial – Interstate 02 Principal Arterial – Other 06 Minor Arterial 07 Major Collector 08 Minor Collector 09 Local Urban 11 Principal Arterial – Interstate 12 Principal Arterial – Other Freeways or Expressways 14 Other Principal Arterial 16 Minor Arterial 17 Collector 19 Local
#27 Year Built	several	Code the year in 4 digits.
#42 Type of service	0-9	Code / #42A Service on Bridge / #42B Service under Bridge 1 Highway 2 Railroad 3 Pedestrian-bicycle 4 Highway-railroad 5 Highway-pedestrian 6 Overpass structure at an interchange or second level or a multilevel interchange 7 Third level (Interchange) 8 Fourth level (Interchange) 9 Building or plaza 0 Other

#43A Kind of material and/or design	0-9	Code	Description
		1	Concrete
		2	Concrete continuous
		3	Steel
		4	Steel continuous
		5	Prestressed concrete
		6	Prestressed concrete continuous
		7	Wood or Timber
		8	Masonry
		9	Aluminum, Wrought Iron or Cast Iron
		0	Other
#43B Structure type	several	Code	Description
		01	Slab
		02	Stringer/Multi-beam or Girder
		03	Girder and Floorbeam System
		04	Tee Beam
		05	Box Beam or Girders – Multiple
		06	Box Beam or Girders – Single or Spread
		07	Frame
		08	Orthotropic
		09	Truss – Deck
		10	Truss – Thru
		11	Arch – Deck
		12	Arch – Thru
		13	Suspension
		14	Stayed Girder
		15	Movable – Lift
		16	Movable – Bascule
		17	Movable – Swing
		18	Tunnel
		19	Culvert
		20	Mixed types
		21	Segmental Box Girder
		22	Channel Beam
		00	Other
#5B Route prefix	1-8	Code	Description
		1	Interstate Highway
		2	U.S. numbered Highway
		3	State Highway
		4	County Highway
		5	City Street
		6	Federal lands road
		7	State lands road
		8	Other

#5C Service level	several	Code / Description 0 None of the below 1 Mainline 2 Alternate 3 Bypass 4 Spur 6 Business 7 Ramp, Wye, Connector, etc. 8 Service and/or unclassified frontage road
#28A/#28B Lanes on/under structure	several	Each two digits for number of lanes on/under structure
#45 Number of spans	several	Three digits for the number of spans.
#48 Maximum span length	several	Length coded in five digits
#49 Structure length	several	Length coded in six digits
#108A Type of wearing surface	0-9, N	Code / Description 1 Monolithic Concrete 2 Integral Concrete 3 Latex Concrete or similar additive 4 Low slump Concrete 5 Epoxy Overlay 6 Bituminous 7 Wood or Timber 8 Gravel 9 Other 0 None N Not Applicable
#108B Type of membrane	several	Code / Description 1 Built-up 2 Preformed Fabric 3 Epoxy 8 Unknown 9 Other 0 None N Not Applicable

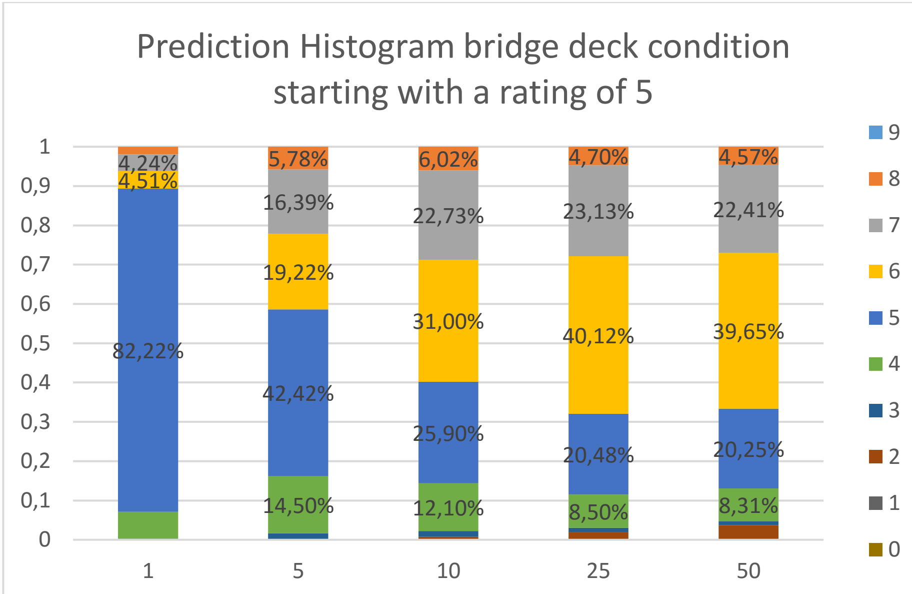
#108C Deck protection	several	<u>Code</u> <u>Description</u> 1 Epoxy coated reinforcing 2 Galvanized reinforcing 3 Other coated reinforcing 4 Cathodic protection 6 Polymer Impregnated 7 Internally Sealed 8 Unknown 9 Other 0 None N Not Applicable
#16 Latitude/#17 Longitude	several	Coded GPS position (XXX degrees XX minutes XX.XX seconds)
Time-variant parameters	**Unit**	
#29 ADT	several	6-digit coded average daily traffic
#109 ADTT	several	2-digit coded percentage that shows percentage of truck traffic included in #29
#91 Designate inspection frequency	several	2-digit code of number of month between two inspections
#70 Bridge posting	0-5	<u>Code</u> <u>Relationship or Operating Rating to Maximum Legal Load</u> 5 Equal to or above legal loads 4 0.1-9.9% below 3 10.0-19.9% below 2 20.0-29.9% below 1 30.0-39.9% below 0 > 39.9% below
#58 Deck rating	0-9, N	<u>Code</u> <u>Description</u> N Not Applicable 9 Excellent condition 8 Very good condition 7 Good condition 6 Satisfactory condition 5 Fair condition 4 Poor condition 3 Serious condition 2 Critical condition 1 "Imminent" failure condition 0 Failed condition
#59 Superstructure rating	0-9, N	See deck rating

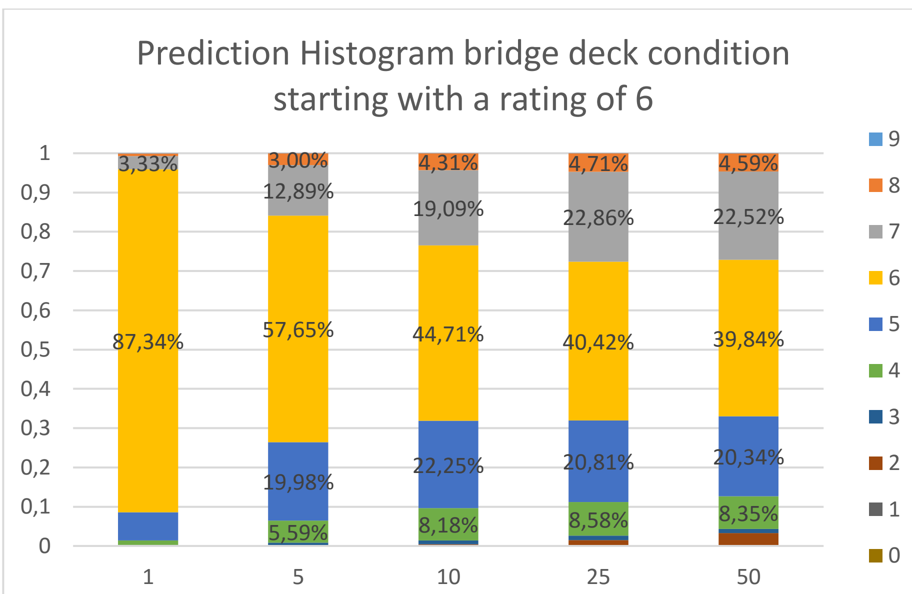
#60 Substructure rating	0-9, N	See deck rating

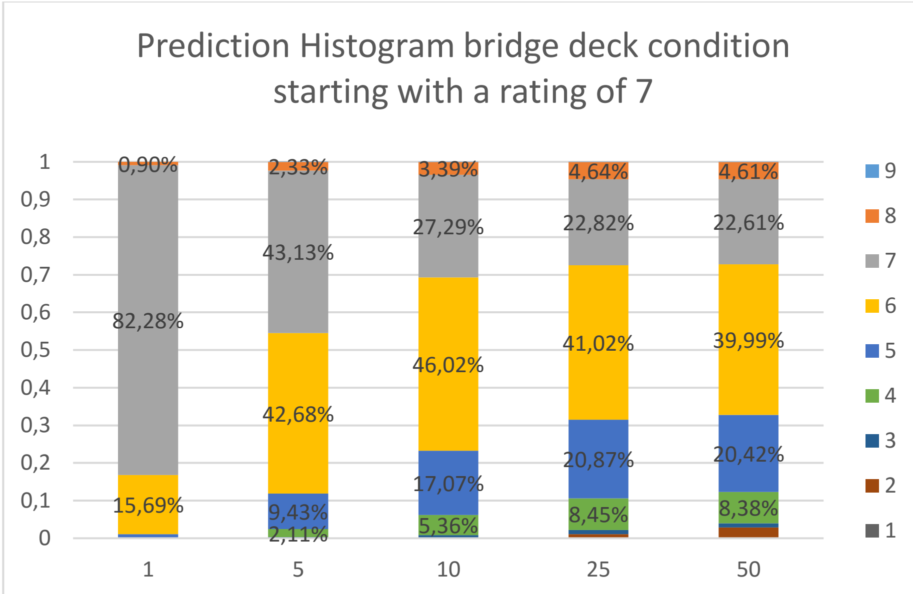
This table was built using the following sources: [7], [8]

Appendix F. Prediction Histograms

Prediction Histograms for bridge deck condition

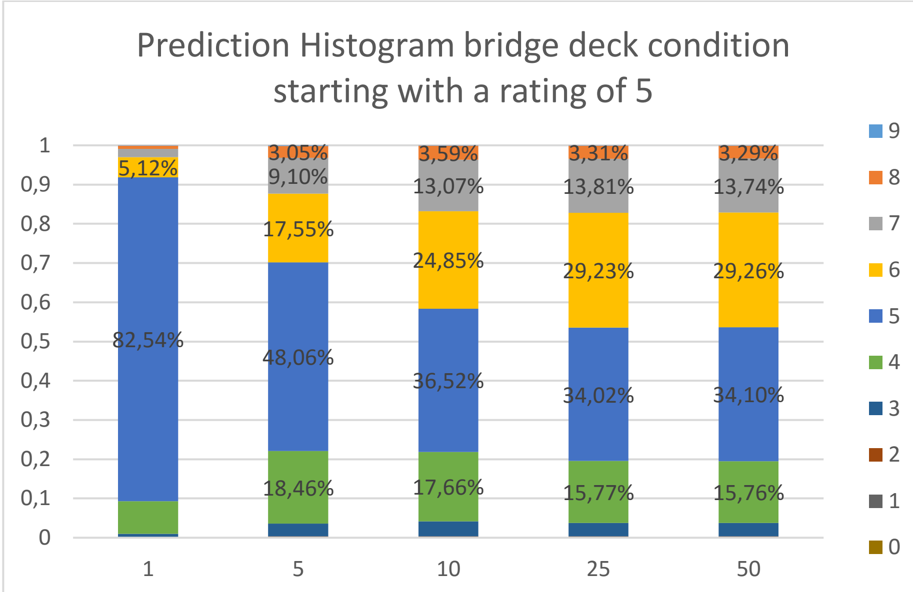


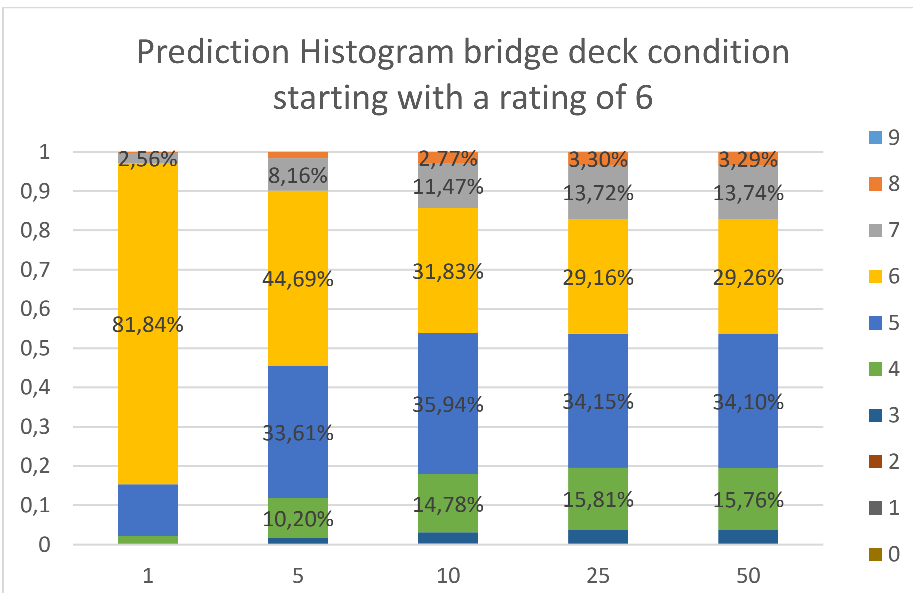


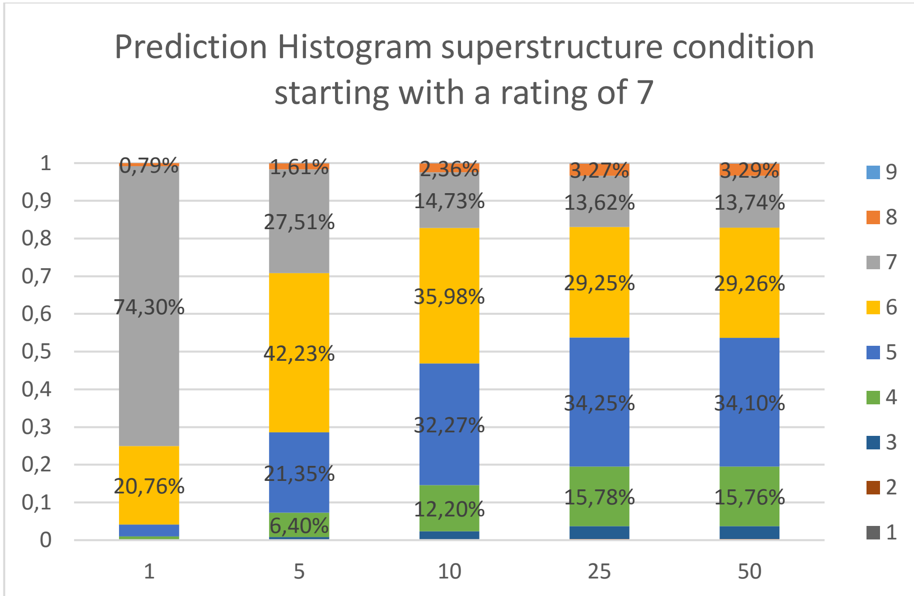


Prediction Histogram bridge deck condition starting with a rating of 7
1
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
0,90%
82,28%
15,69%
2,33%
43,13%
42,68%
9,43%
2,11%
3,39%
27,29%
46,02%
17,07%
5,36%
4,64%
22,82%
41,02%
20,87%
8,45%
4,61%
22,61%
39,99%
20,42%
8,38%
1
5
10
25
50
9
8
7
6
5
4
3
2
1

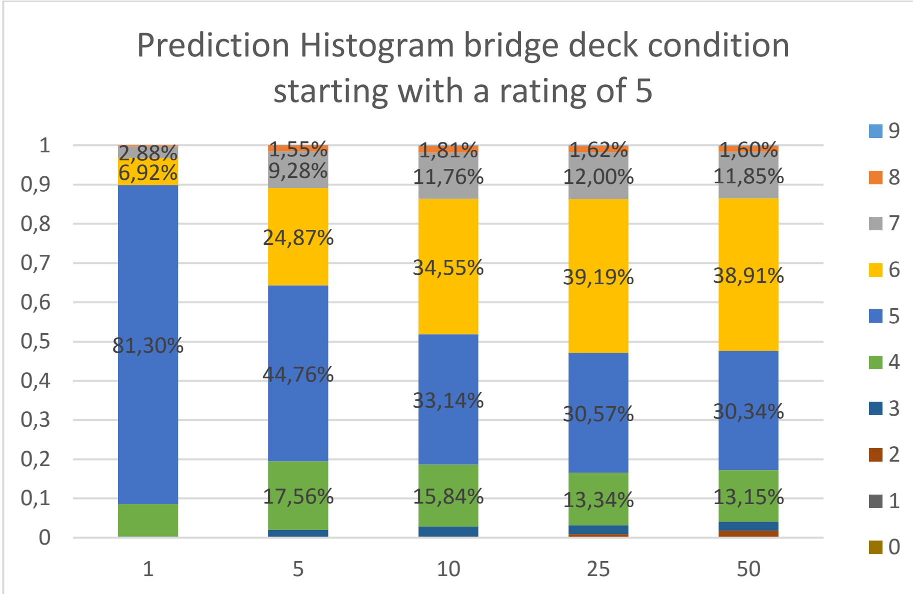
Prediction Histograms for superstructure condition

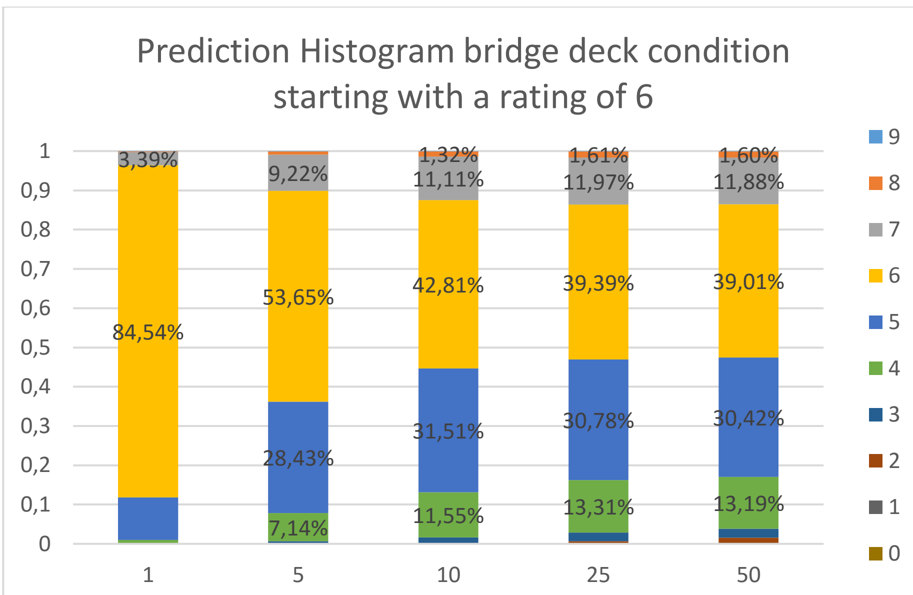


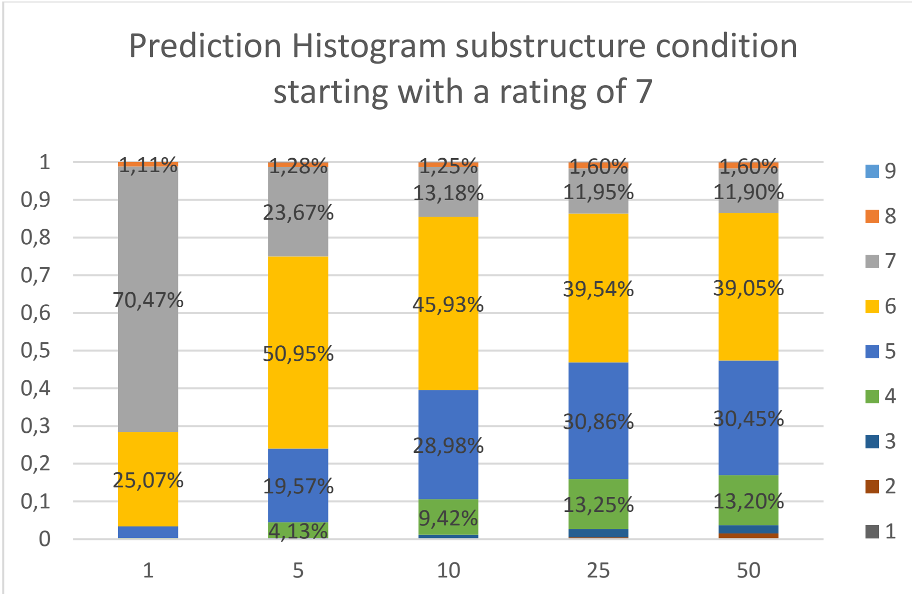



Prediction Histogram superstructure condition starting with a rating of 7
1
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
0,79%
74,30%
20,76%
1,61%
27,51%
42,23%
21,35%
6,40%
2,36%
14,73%
35,98%
32,27%
12,20%
3,27%
13,62%
29,25%
34,25%
15,78%
3,29%
13,74%
29,26%
34,10%
15,76%
1
5
10
25
50
9
8
7
6
5
4
3
2
1

Prediction Histograms for substructure condition

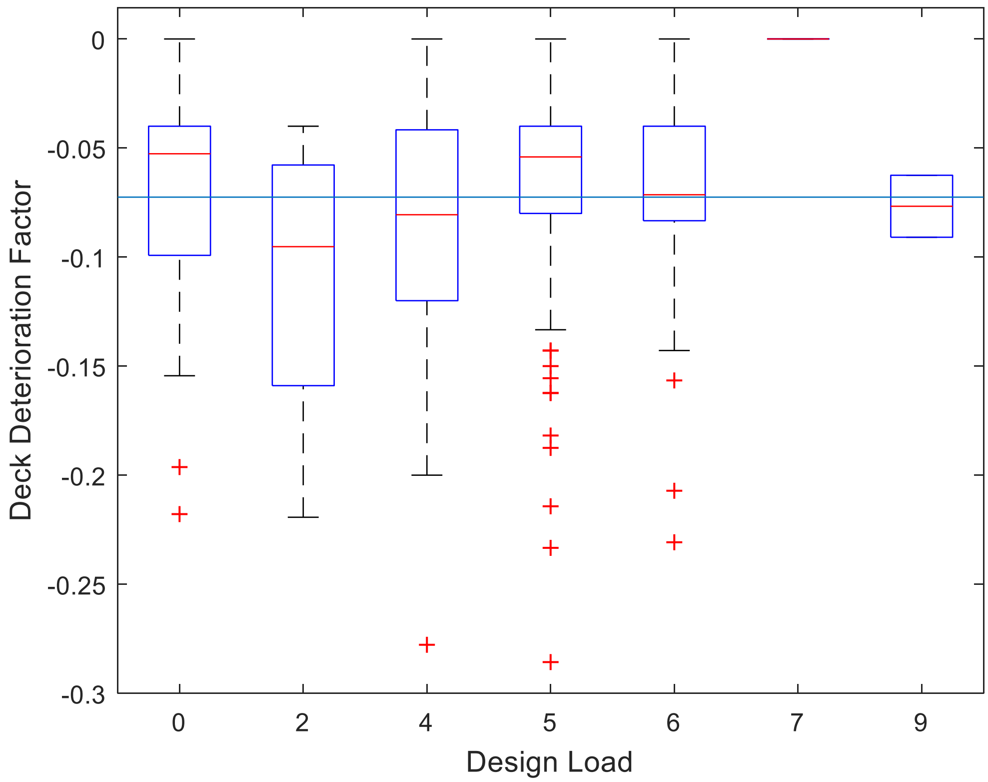


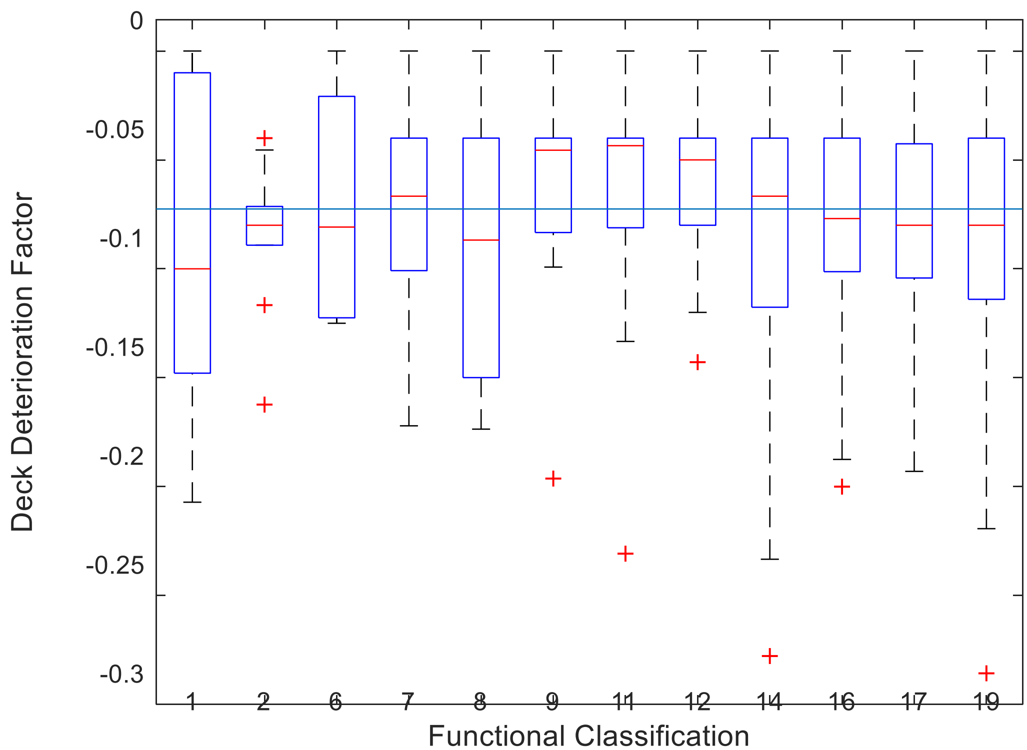


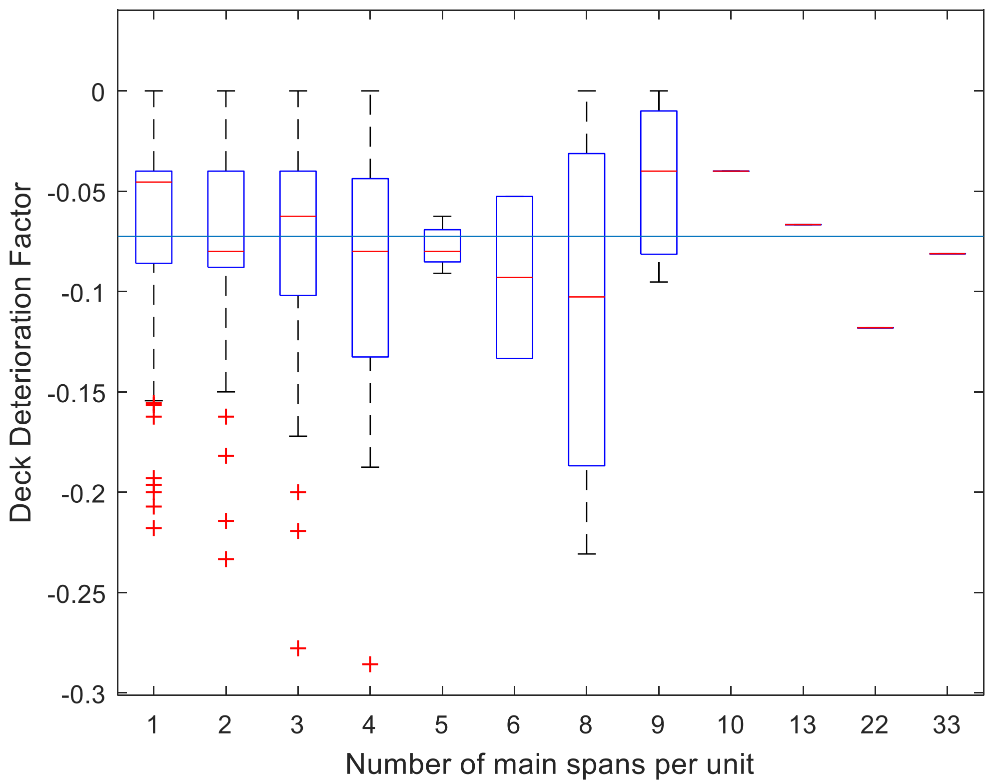


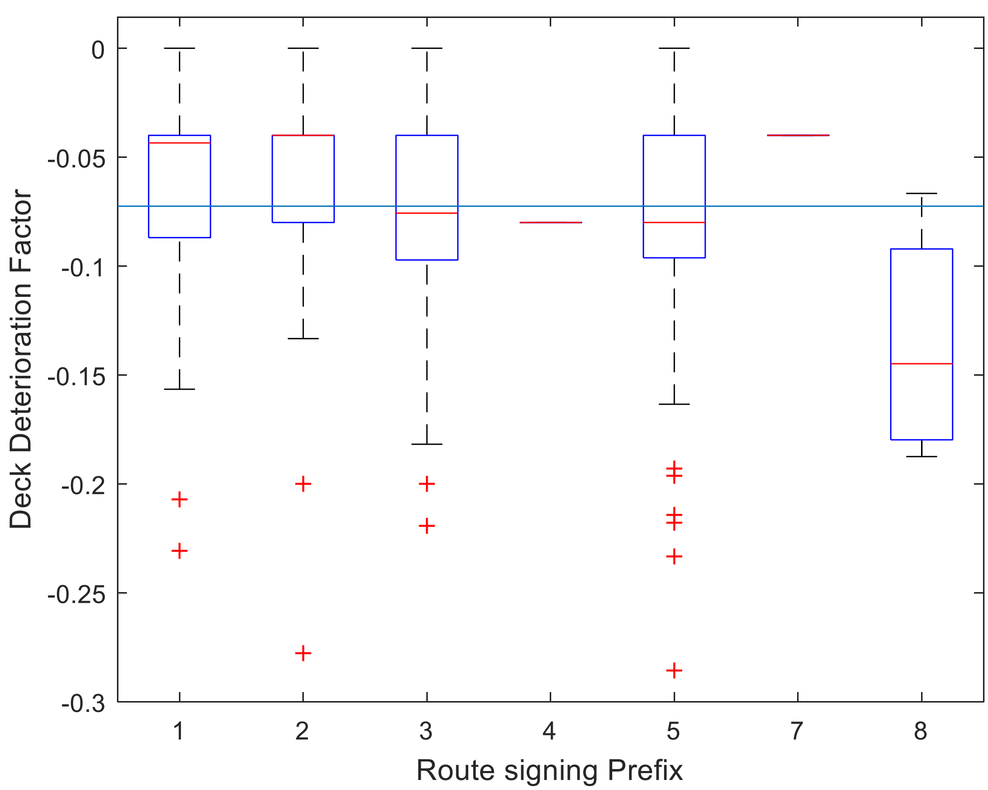
Prediction Histogram substructure condition starting with a rating of 7
1
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
1,11%
70,47%
25,07%
1,28%
23,67%
50,95%
19,57%
4,13%
1,25%
13,18%
45,93%
28,98%
9,42%
1,60%
11,95%
39,54%
30,86%
13,25%
1,60%
11,90%
39,05%
30,45%
13,20%
1
5
10
25
50
9
8
7
6
5
4
3
2
1

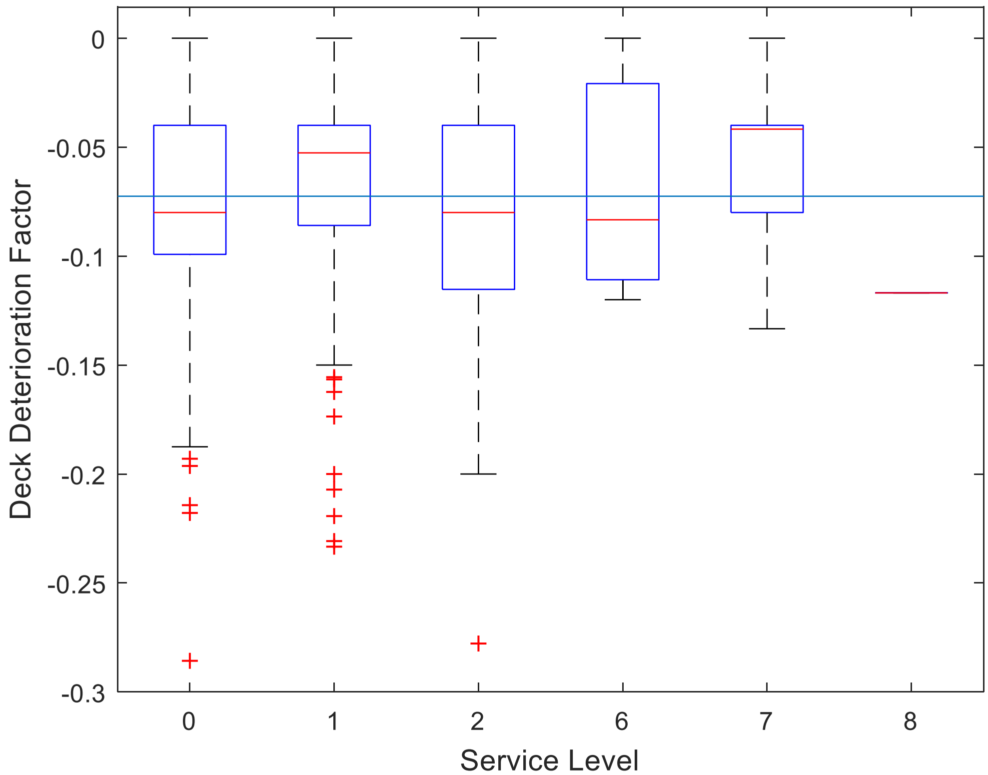
Appendix G. Figures for Bridge deck analysis and correlations



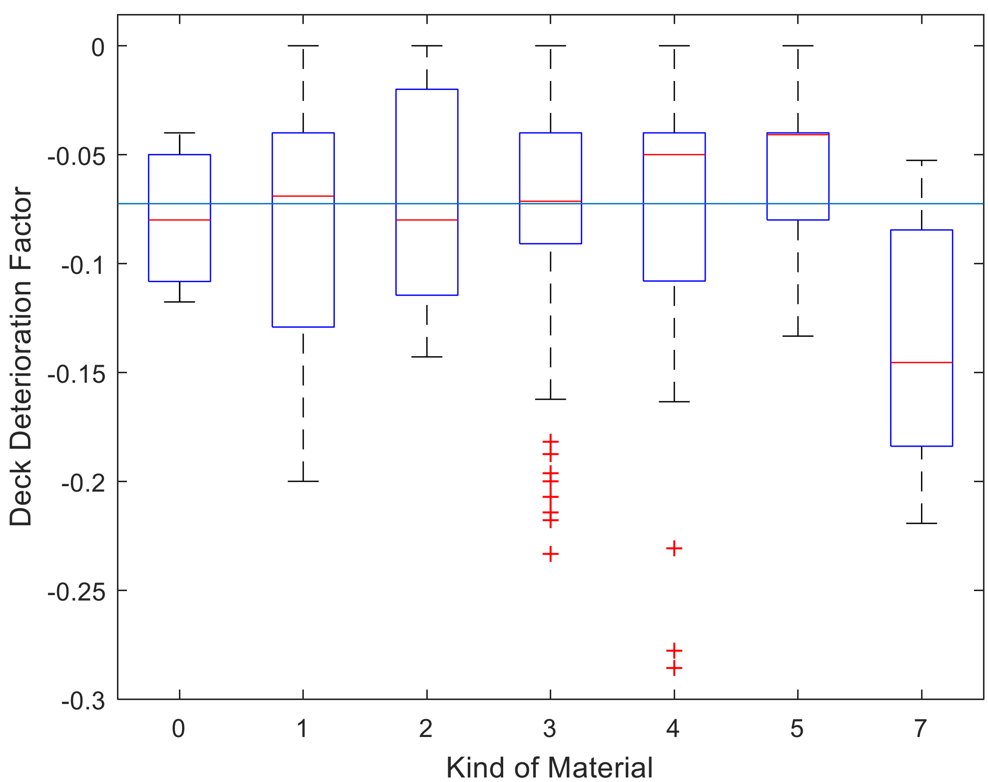



0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
Deck Deterioration Factor
1
2
3
4
5
6
8
9
10
13
22
33
Number of main spans per unit

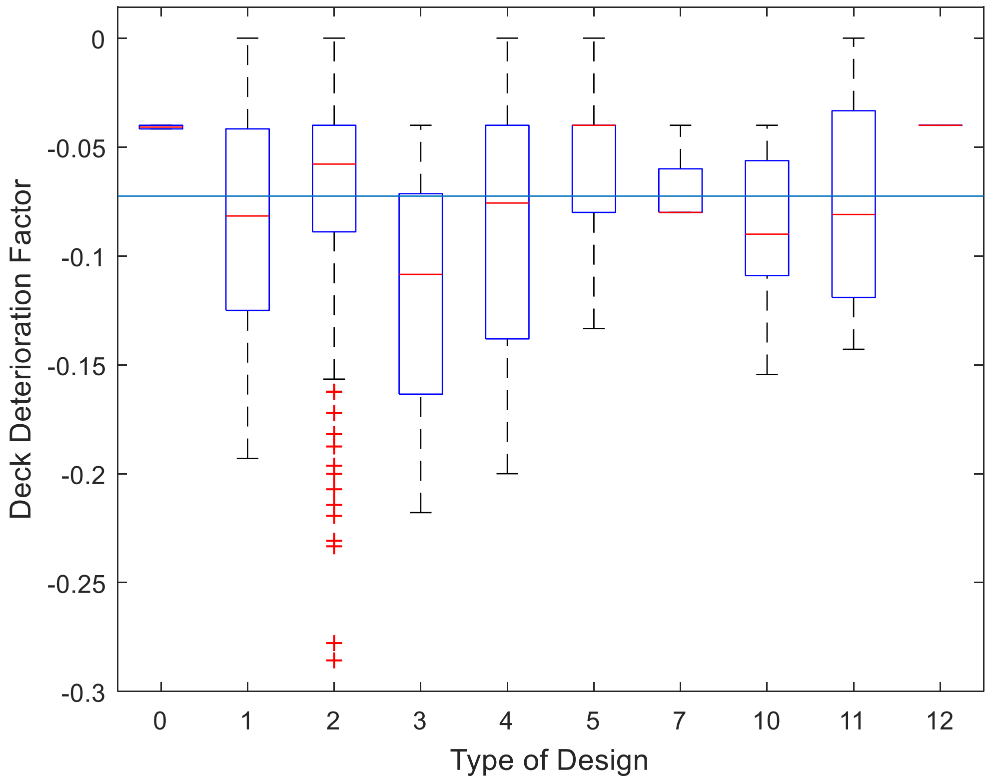

0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
Deck Deterioration Factor
1
2
3
4
5
7
8
Route signing Prefix

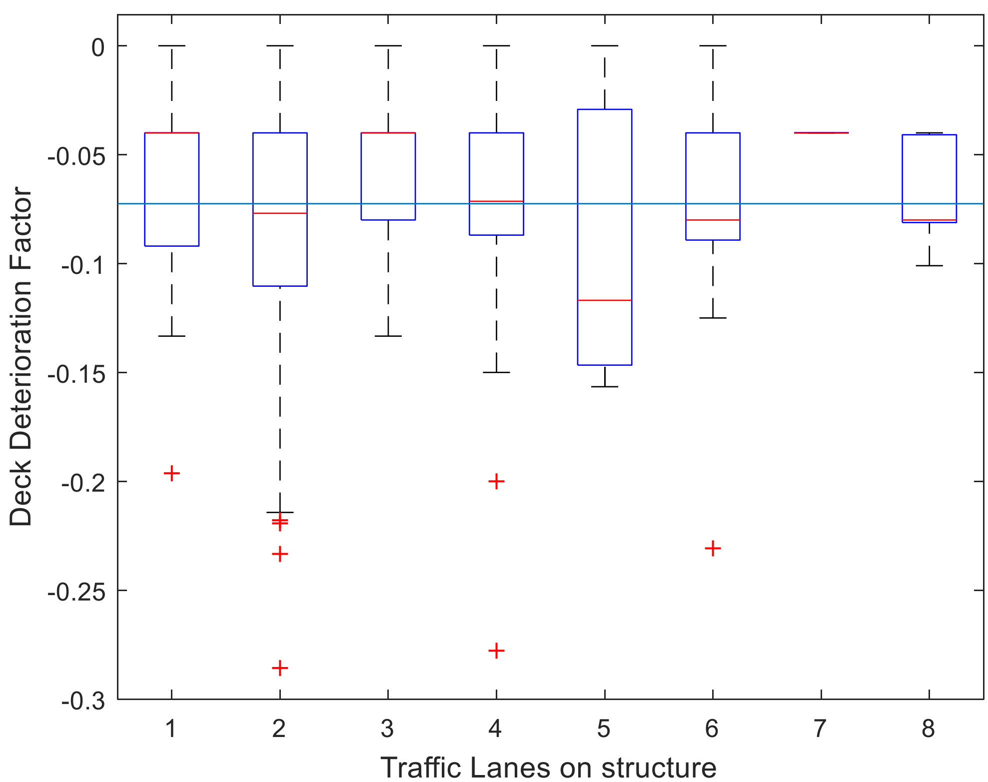


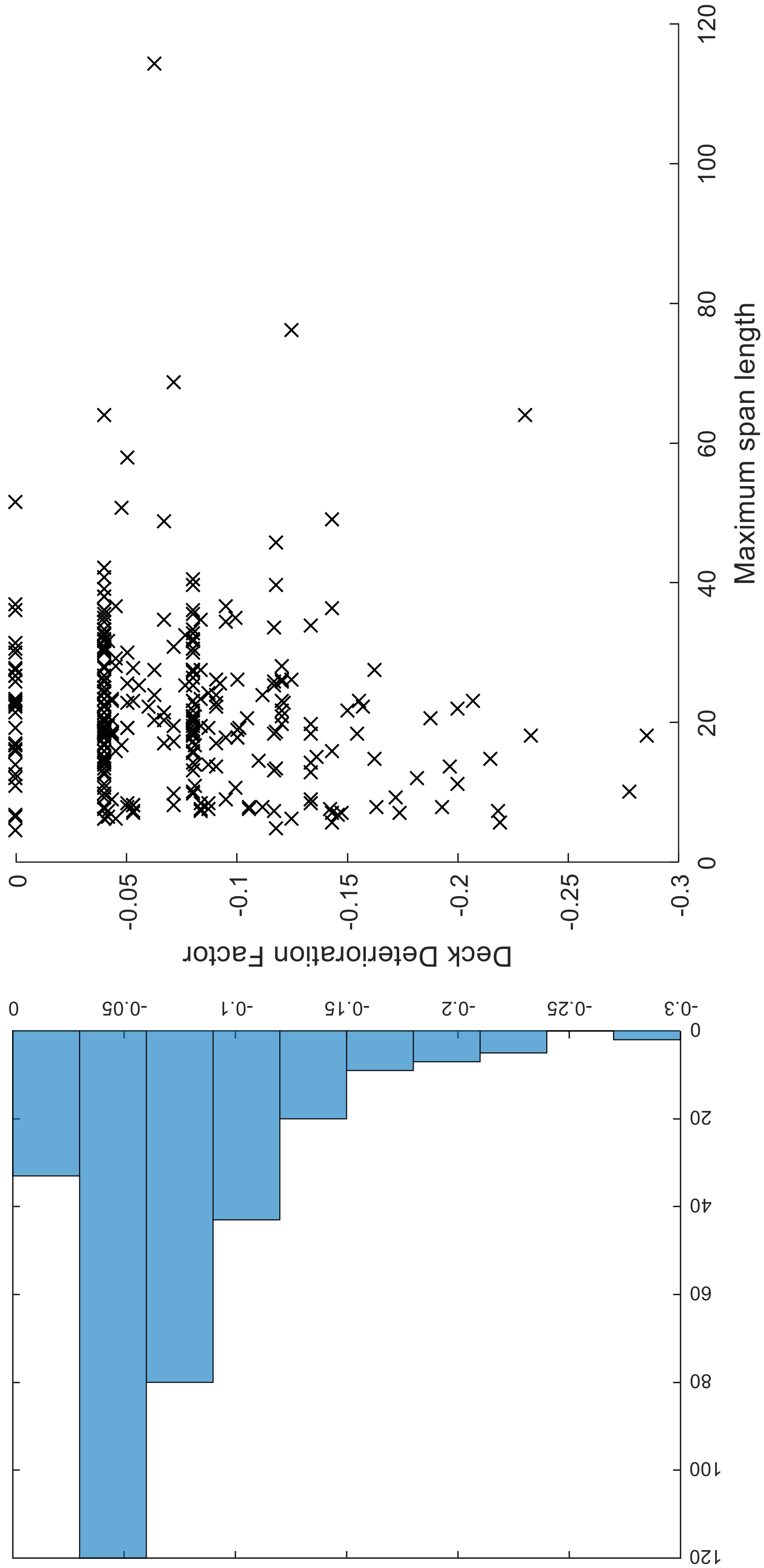
Deck Deterioration Factor
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
0
1
2
6
7
8
Service Level



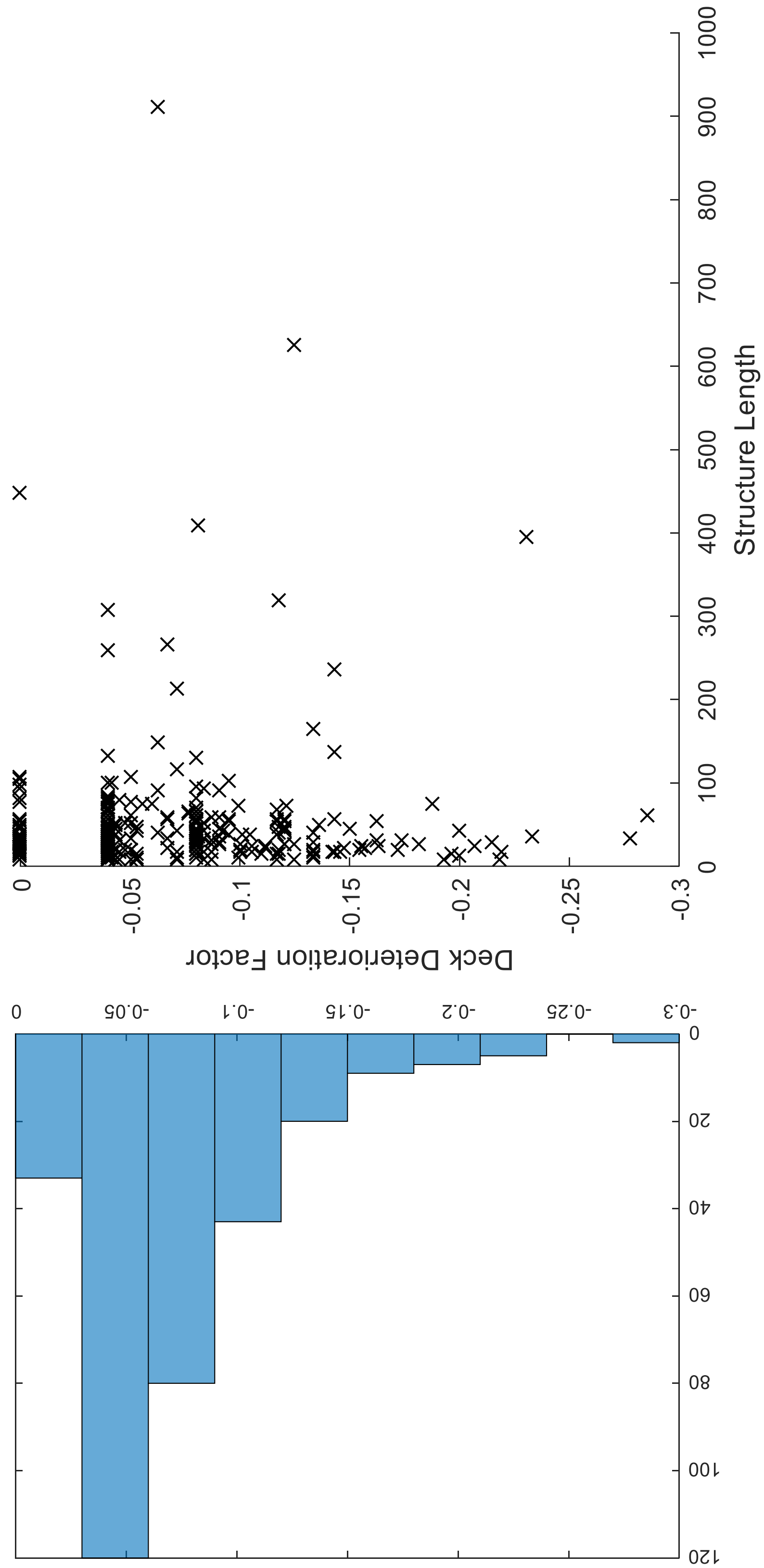
Deck Deterioration Factor
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
0
1
2
3
4
5
7
Kind of Material


0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
Deck Deterioration Factor
0
1
2
3
4
5
7
10
11
12
Type of Design


0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
Deck Deterioration Factor
1
2
3
4
5
6
7
8
Traffic Lanes on structure

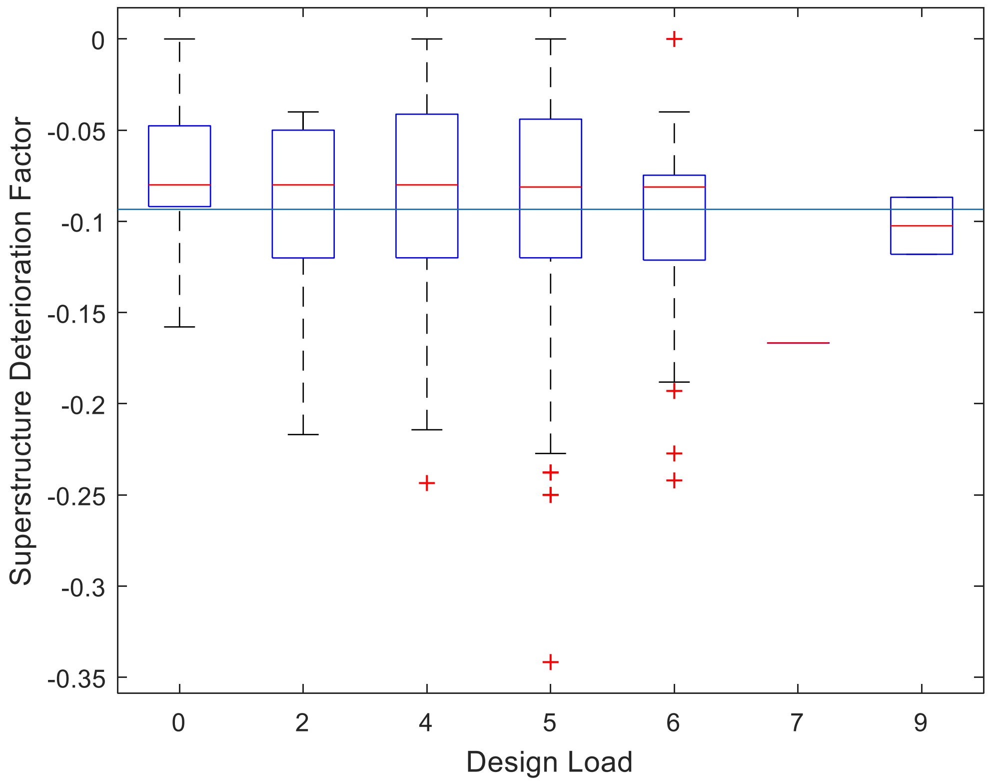


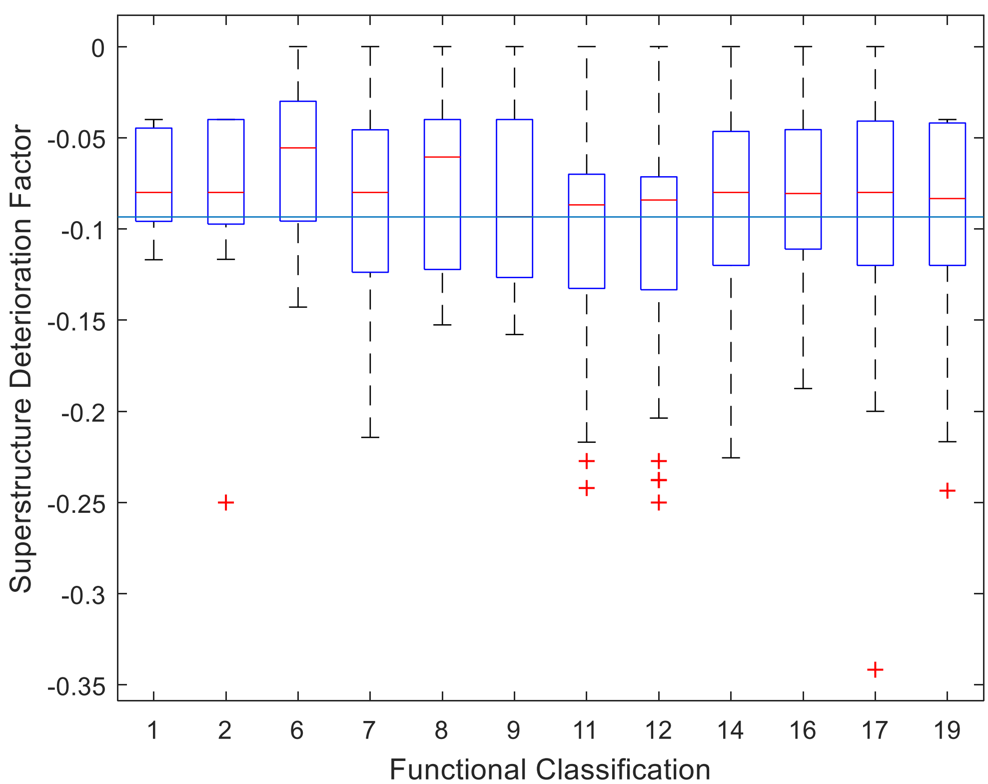
Deck Deterioration Factor
Maximum span length
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
0
20
40
60
80
100
120

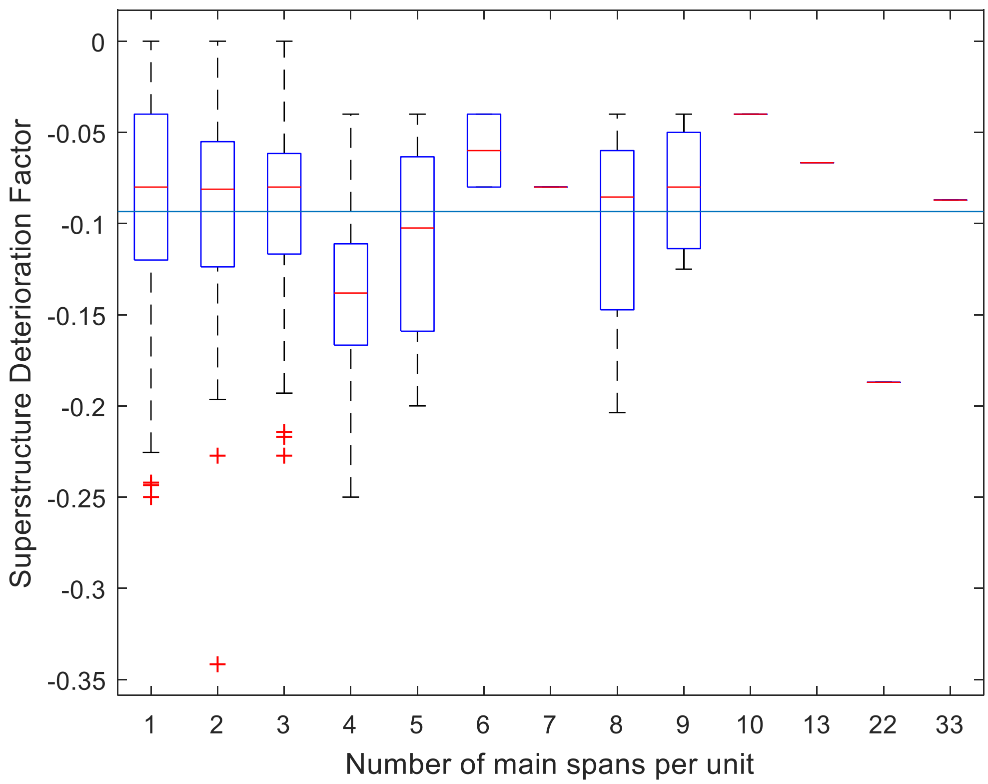


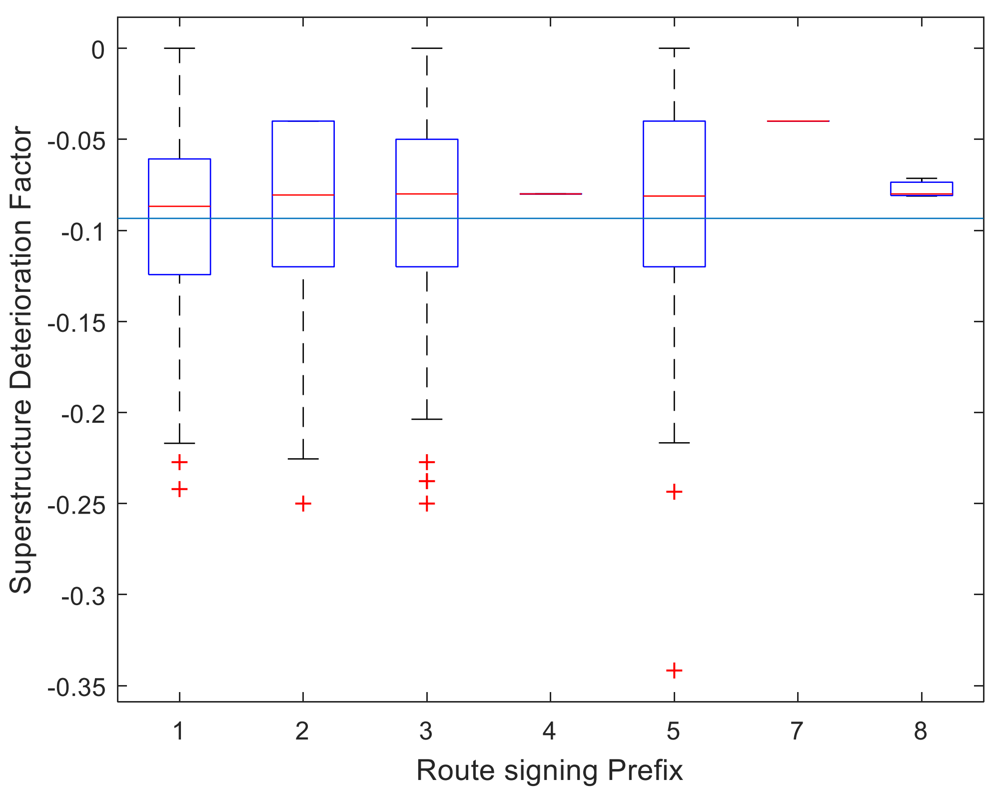
Deck Deterioration Factor
Structure Length

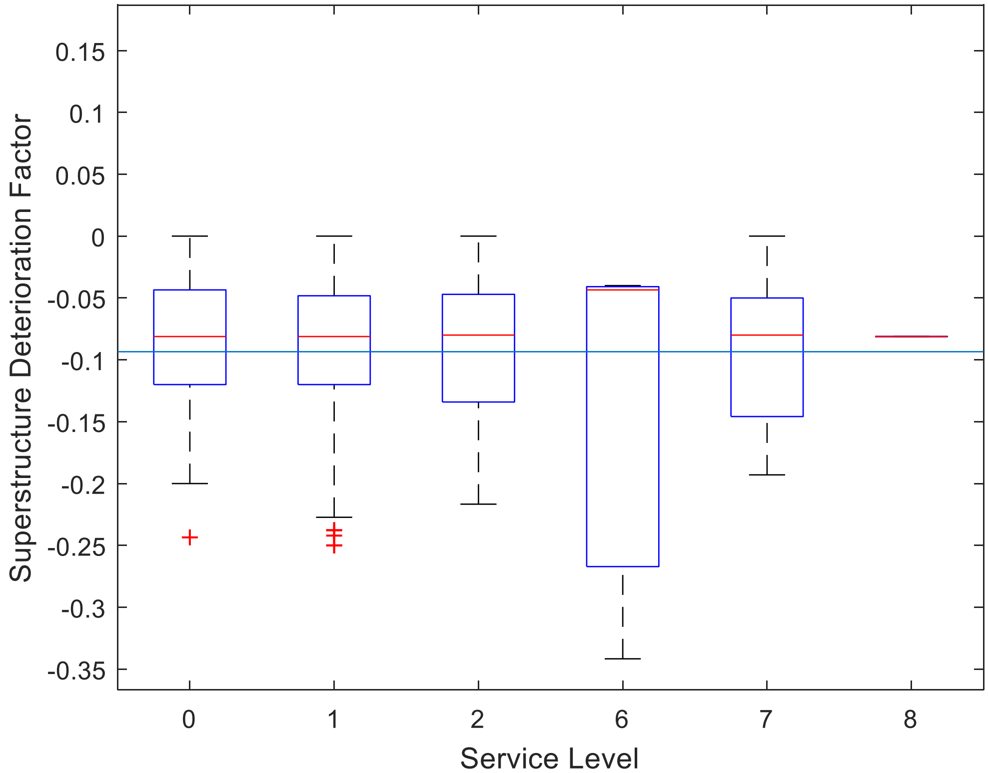
Appendix H. Figures for Superstructure analysis and correlations

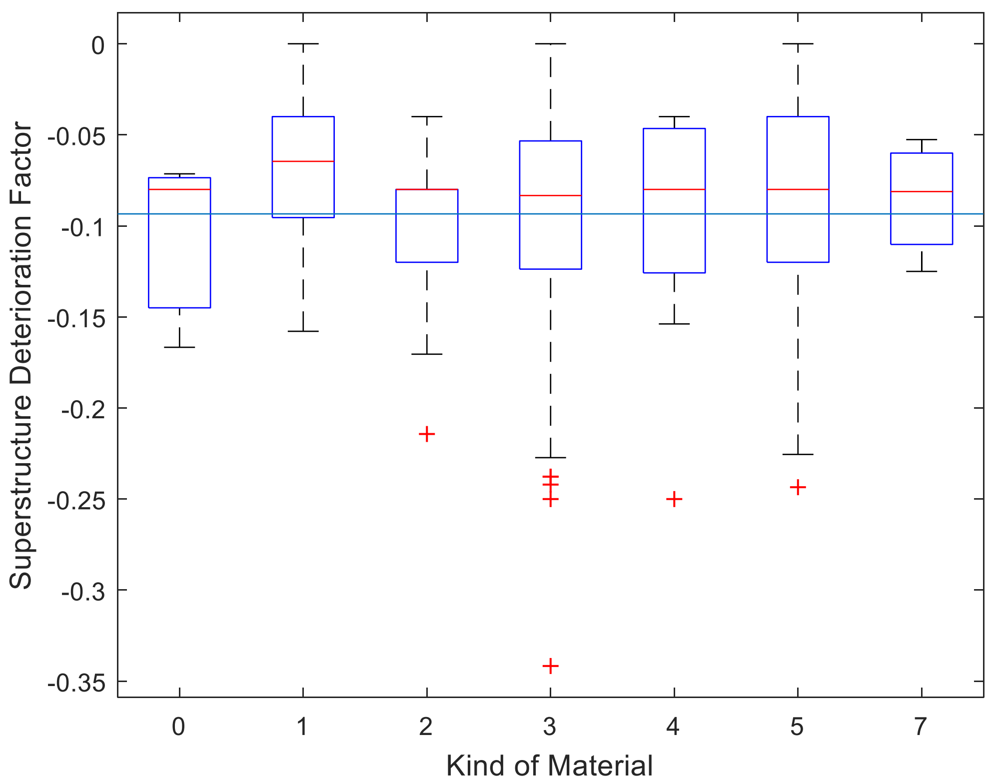


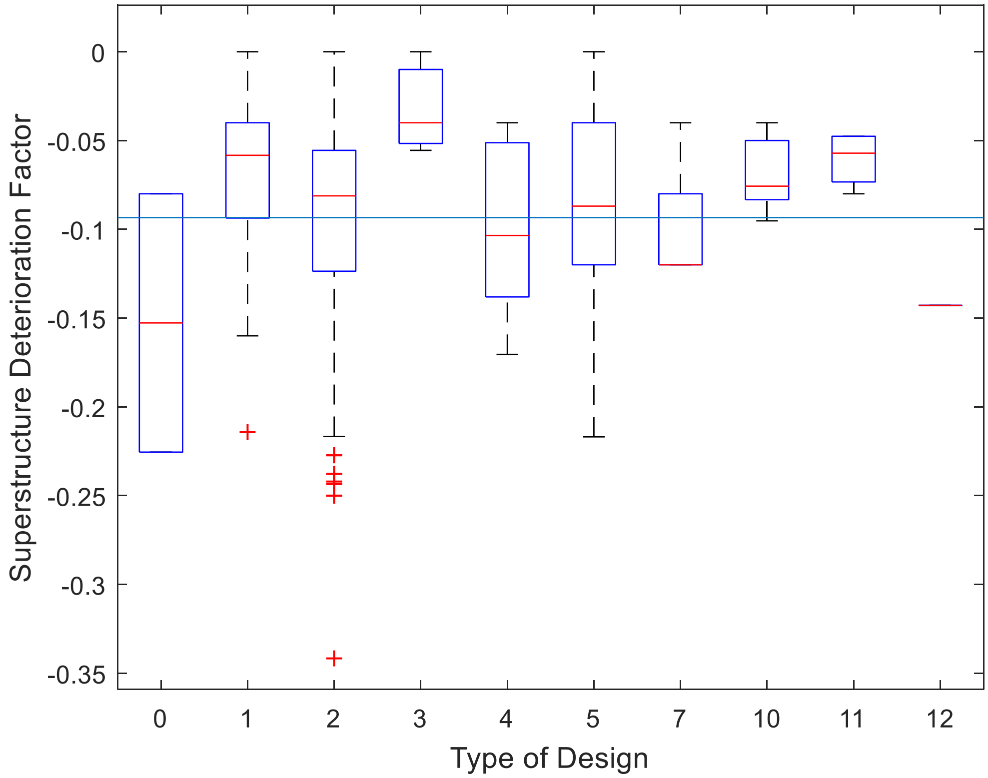


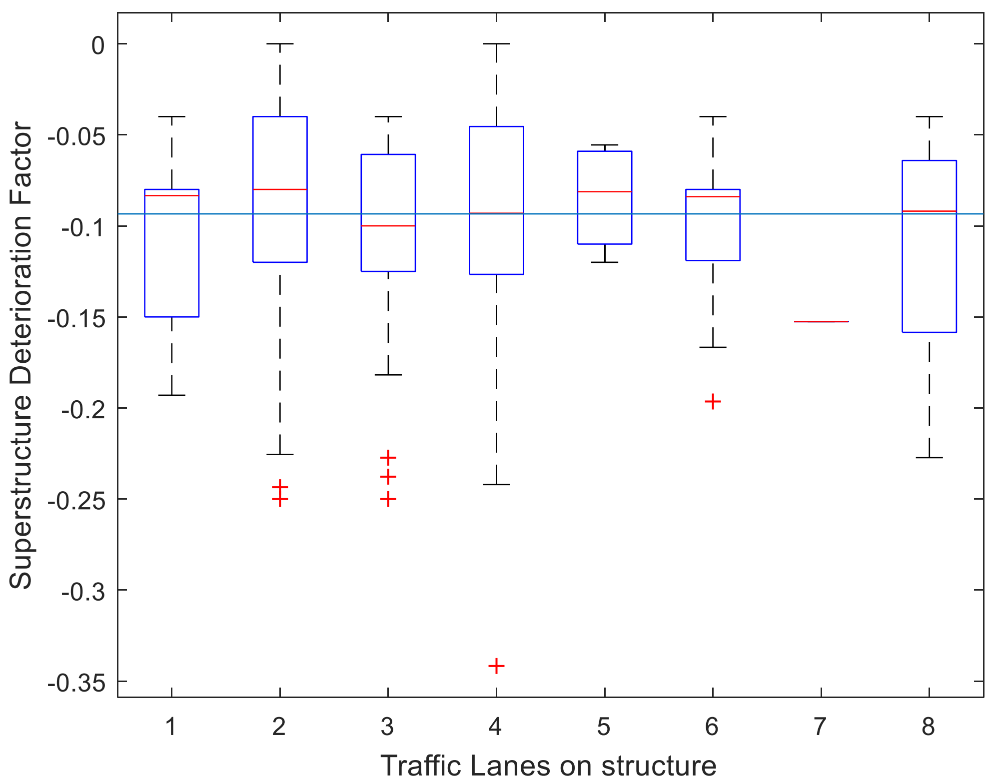

0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
-0.35
Superstructure Deterioration Factor
1 2 3 4 5 6 7 8 9 10 13 22 33
Number of main spans per unit

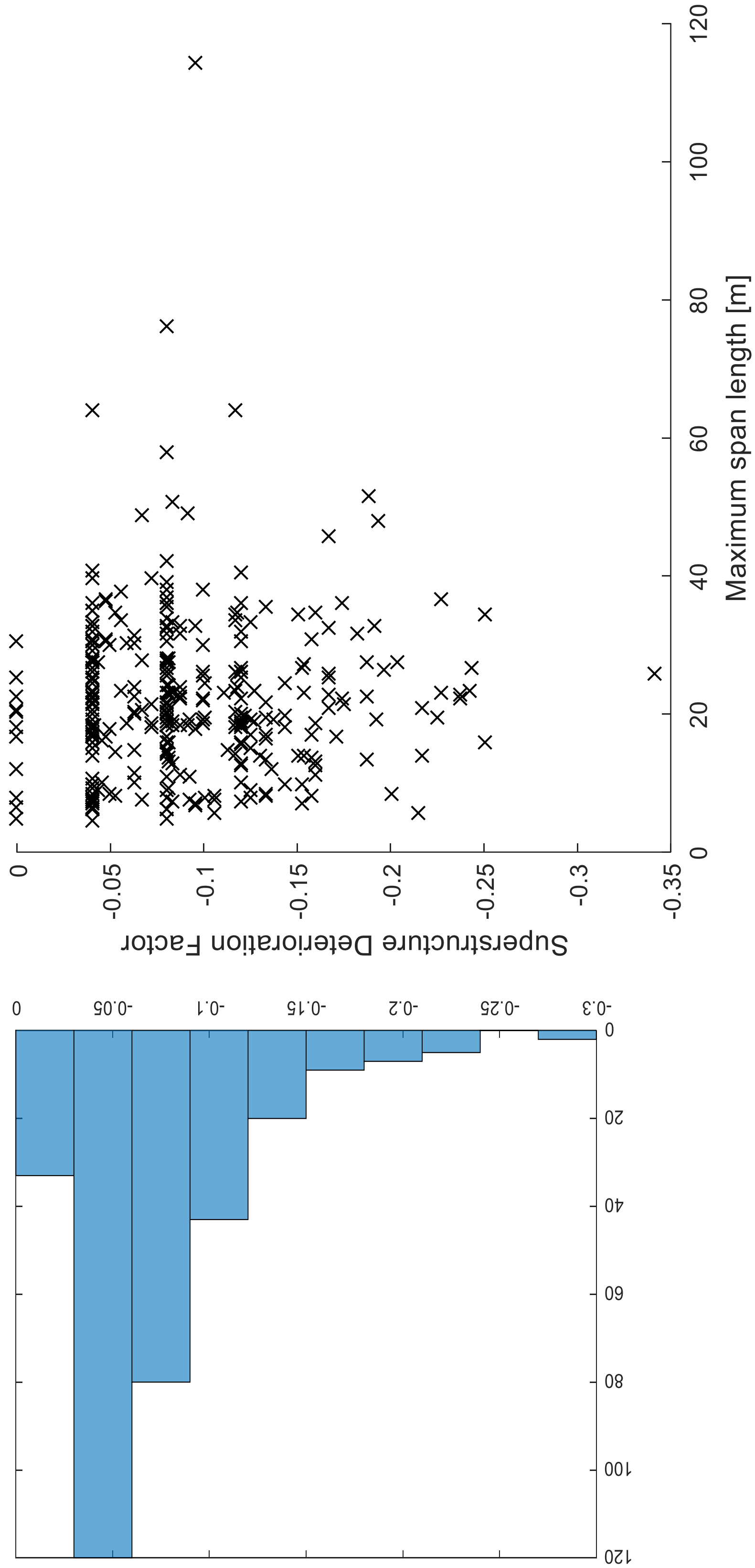

0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
-0.35
Superstructure Deterioration Factor
1 2 3 4 5 7 8
Route signing Prefix

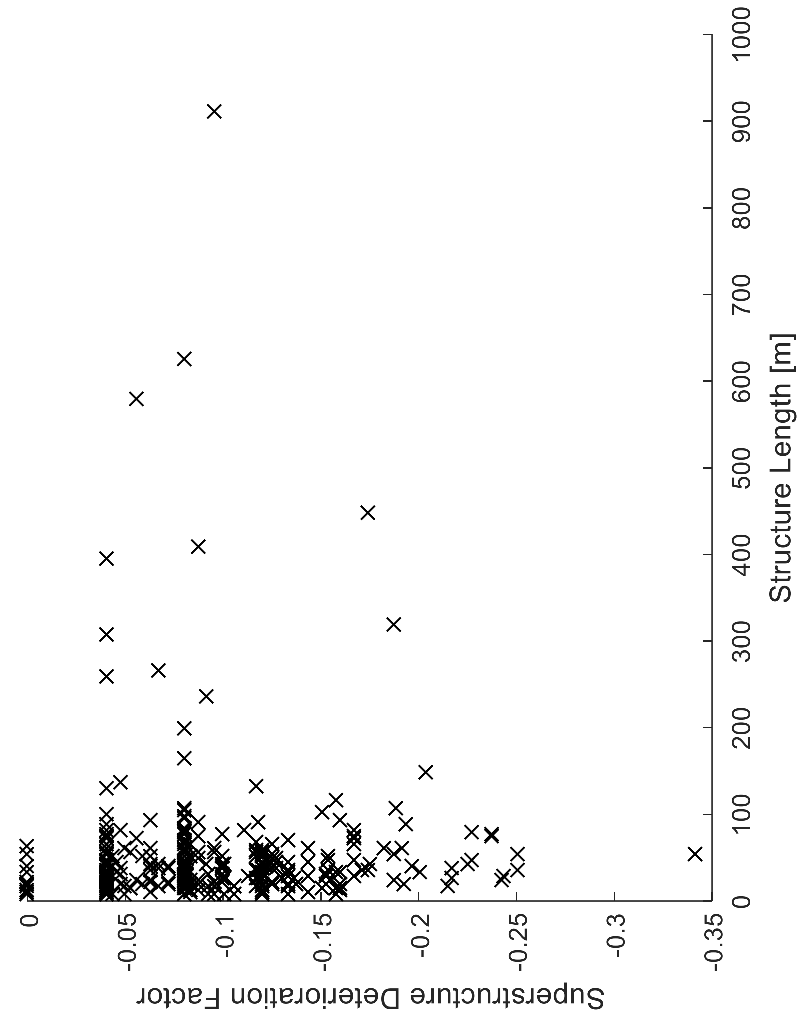

Superstructure Deterioration Factor
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
-0.35
0
1
2
6
7
8
Service Level

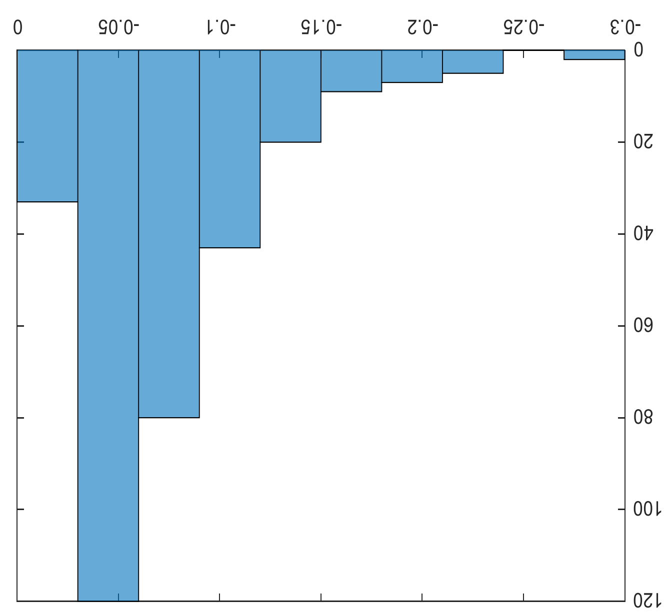

Superstructure Deterioration Factor
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
-0.35
0
1
2
3
4
5
7
Kind of Material

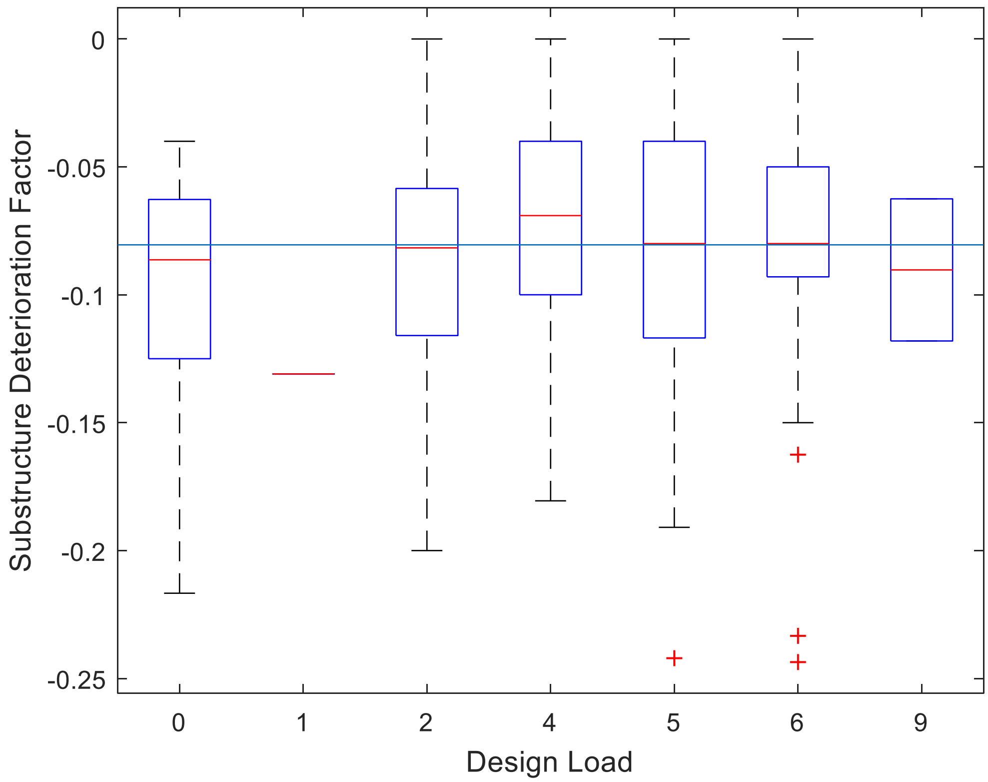

Superstructure Deterioration Factor
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
-0.35
0
1
2
3
4
5
7
10
11
12
Type of Design


Superstructure Deterioration Factor
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
-0.35
1
2
3
4
5
6
7
8
Traffic Lanes on structure


Superstructure Deterioration Factor
Maximum span length [m]


Superstructure Deterioration Factor
Structure Length [m]
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
-0.35
0
100
200
300
400
500
600
700
800
900
1000


0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
0
20
40
60
80
100
120


Substructure Deterioration Factor
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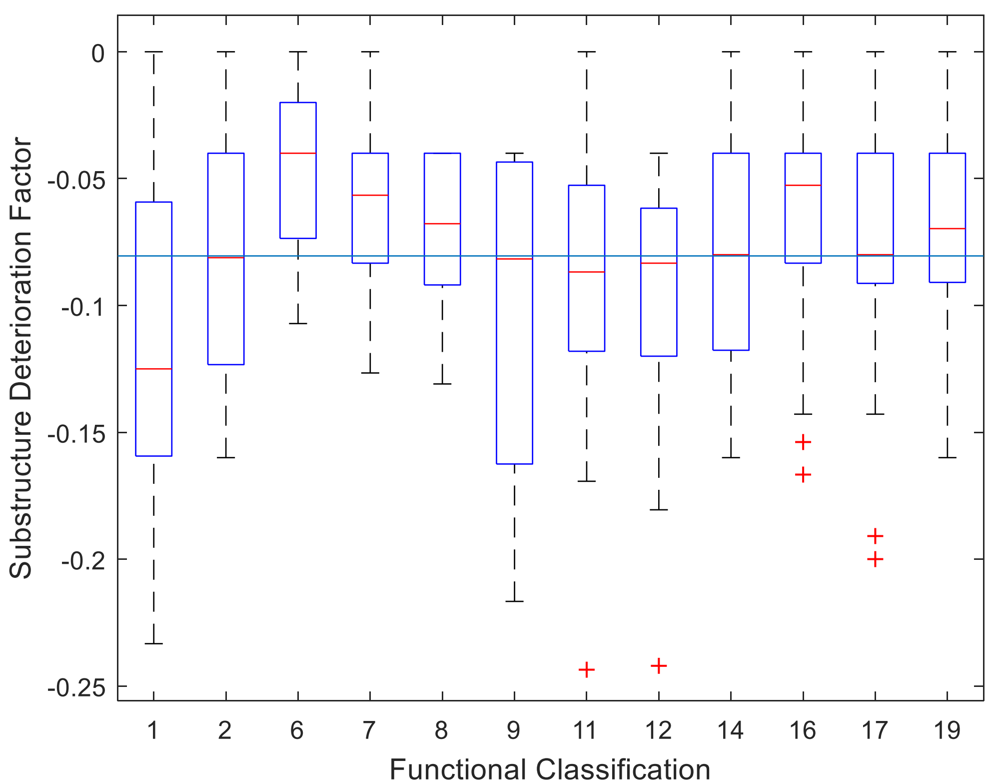
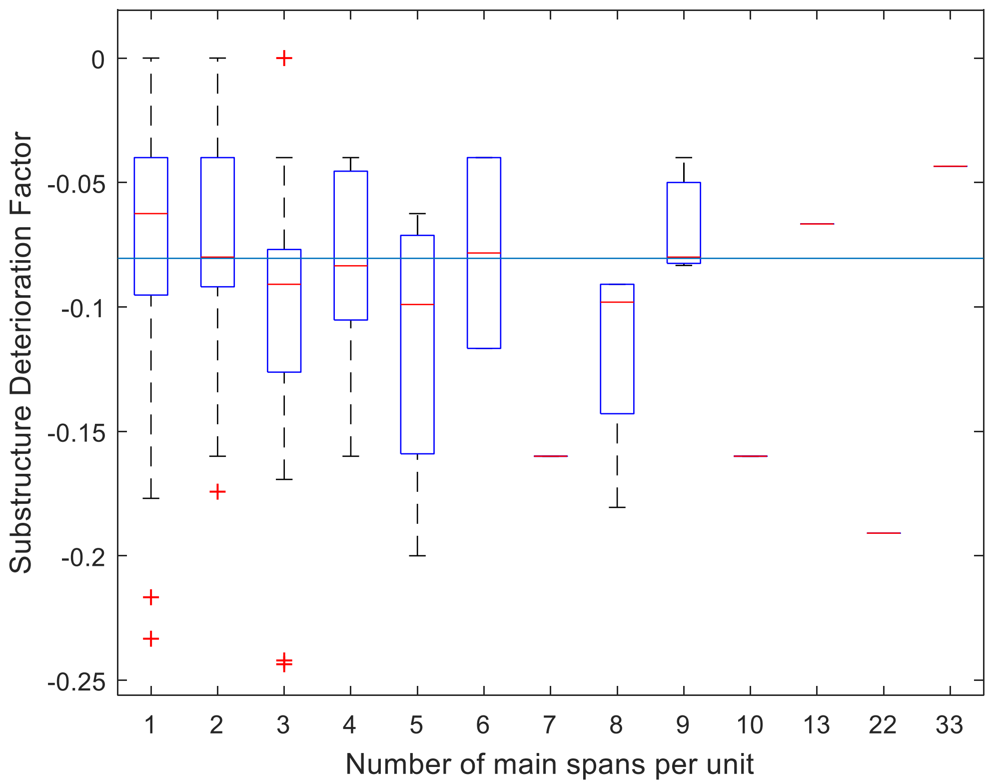
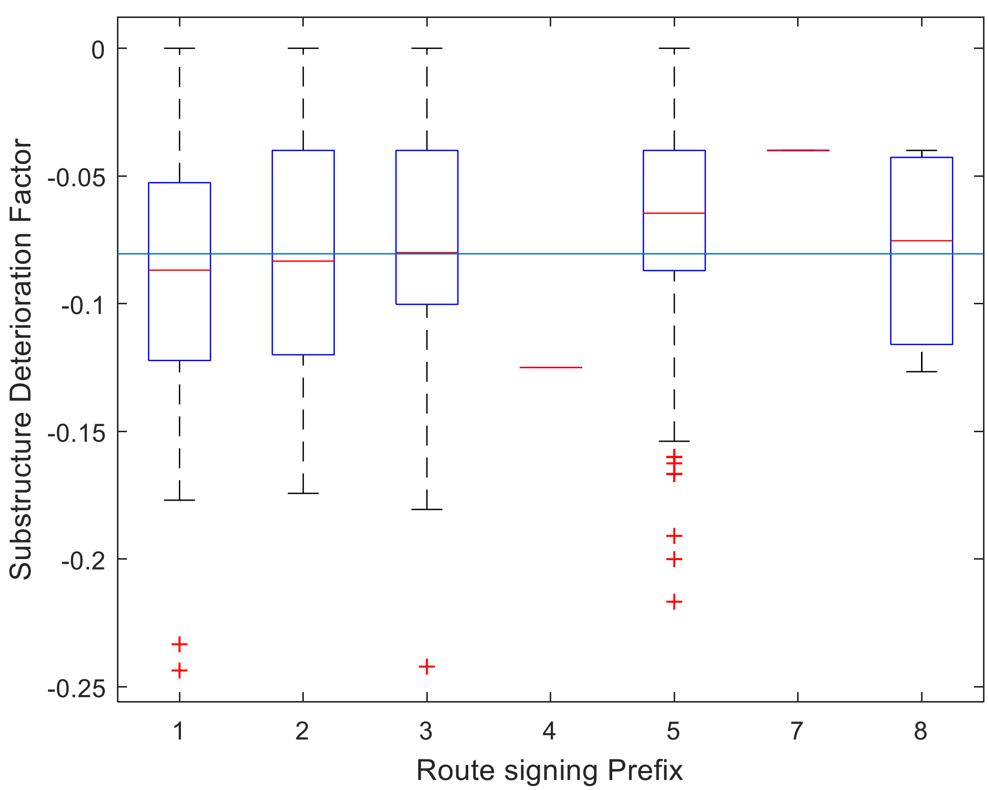
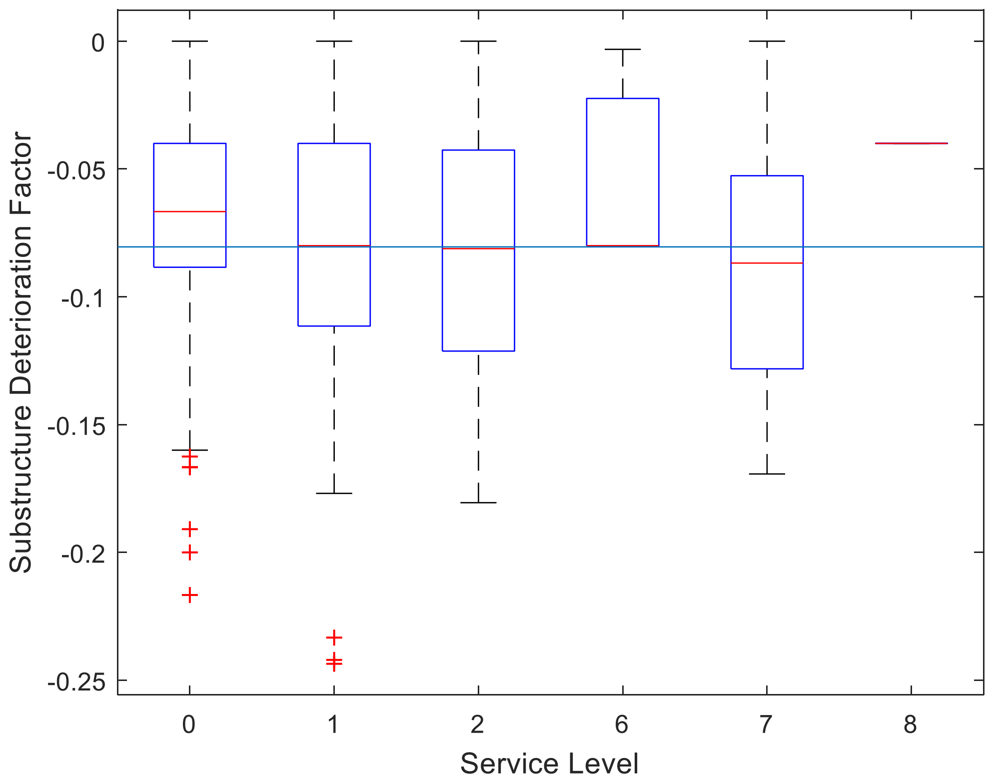
-0.15
-0.2
-0.25
0
1
2
4
5
6
9
Design Load

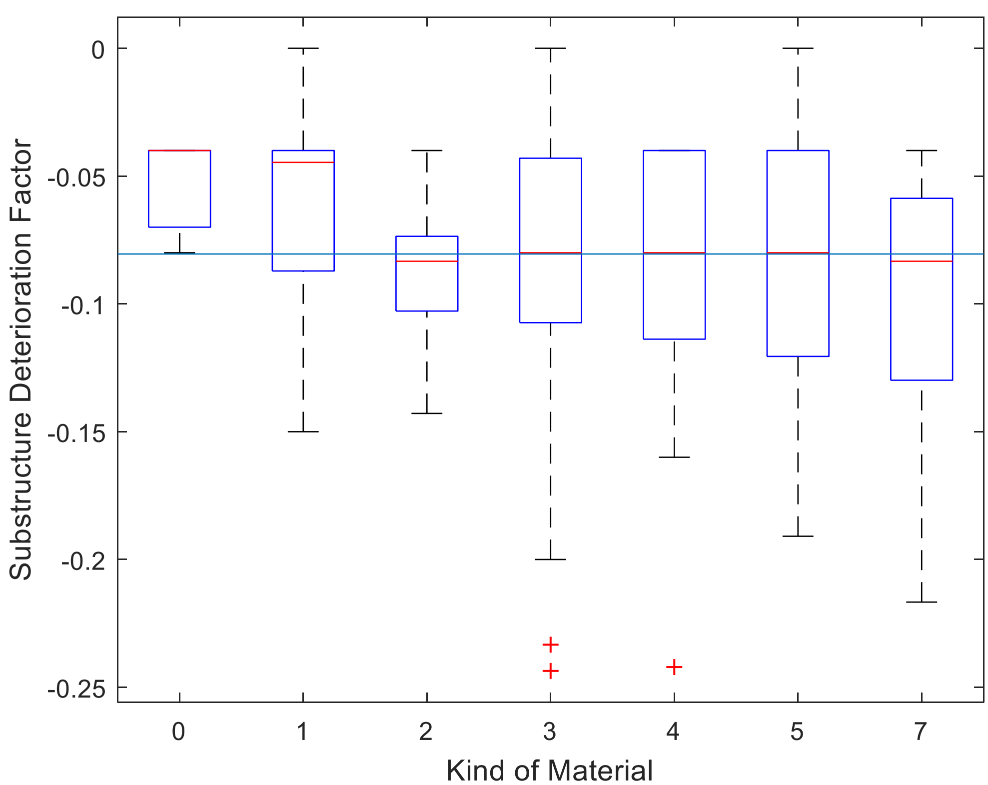

Substructure Deterioration Factor
0
-0.05
-0.1
-0.15
-0.2
-0.25
1
2
6
7
8
9
11
12
14
16
17
19
Functional Classification


0
-0.05
-0.1
-0.15
-0.2
-0.25
Substructure Deterioration Factor
1 2 3 4 5 6 7 8 9 10 13 22 33
Number of main spans per unit

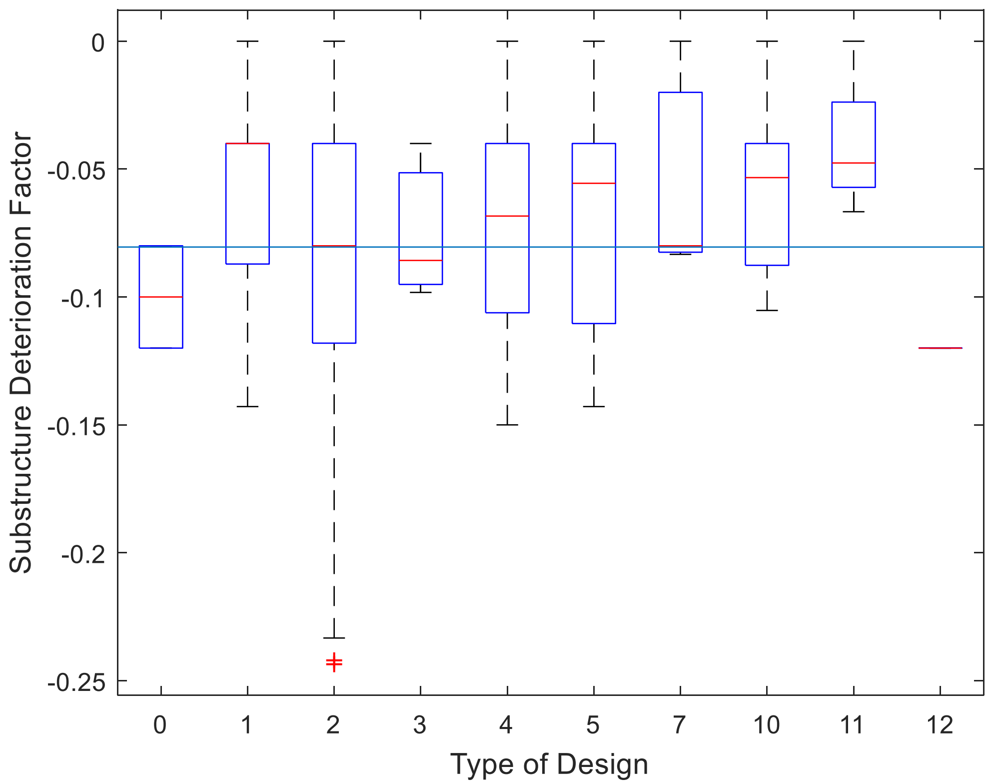

0
-0.05
-0.1
-0.15
-0.2
-0.25
Substructure Deterioration Factor
1 2 3 4 5 7 8
Route signing Prefix

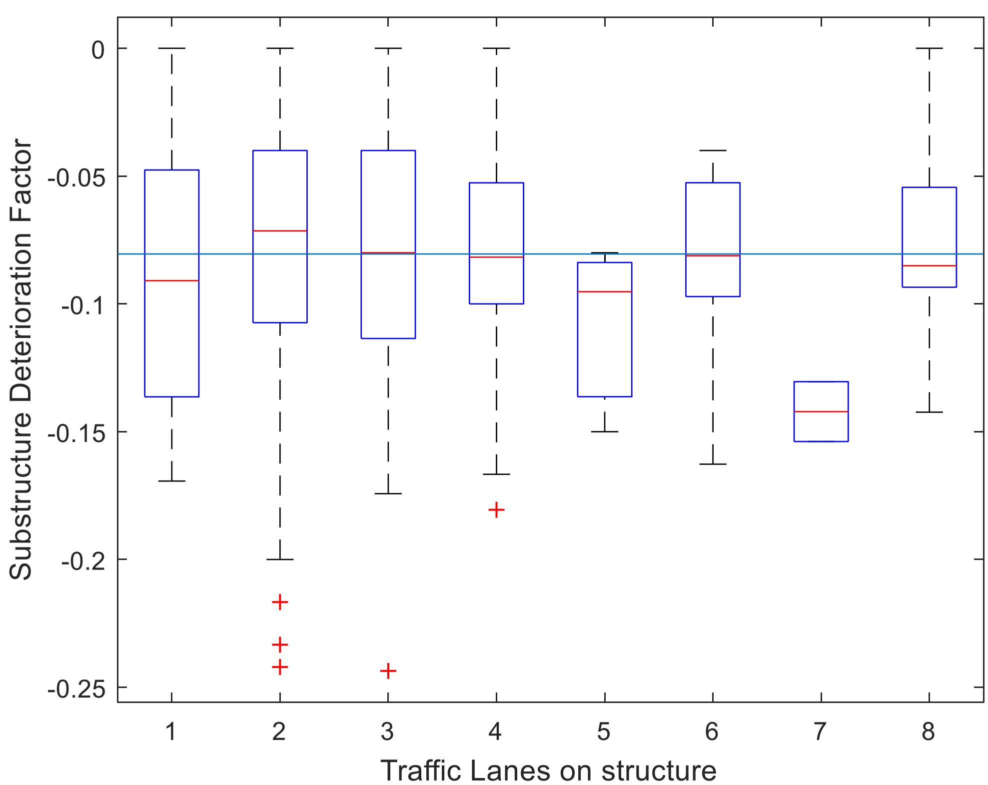


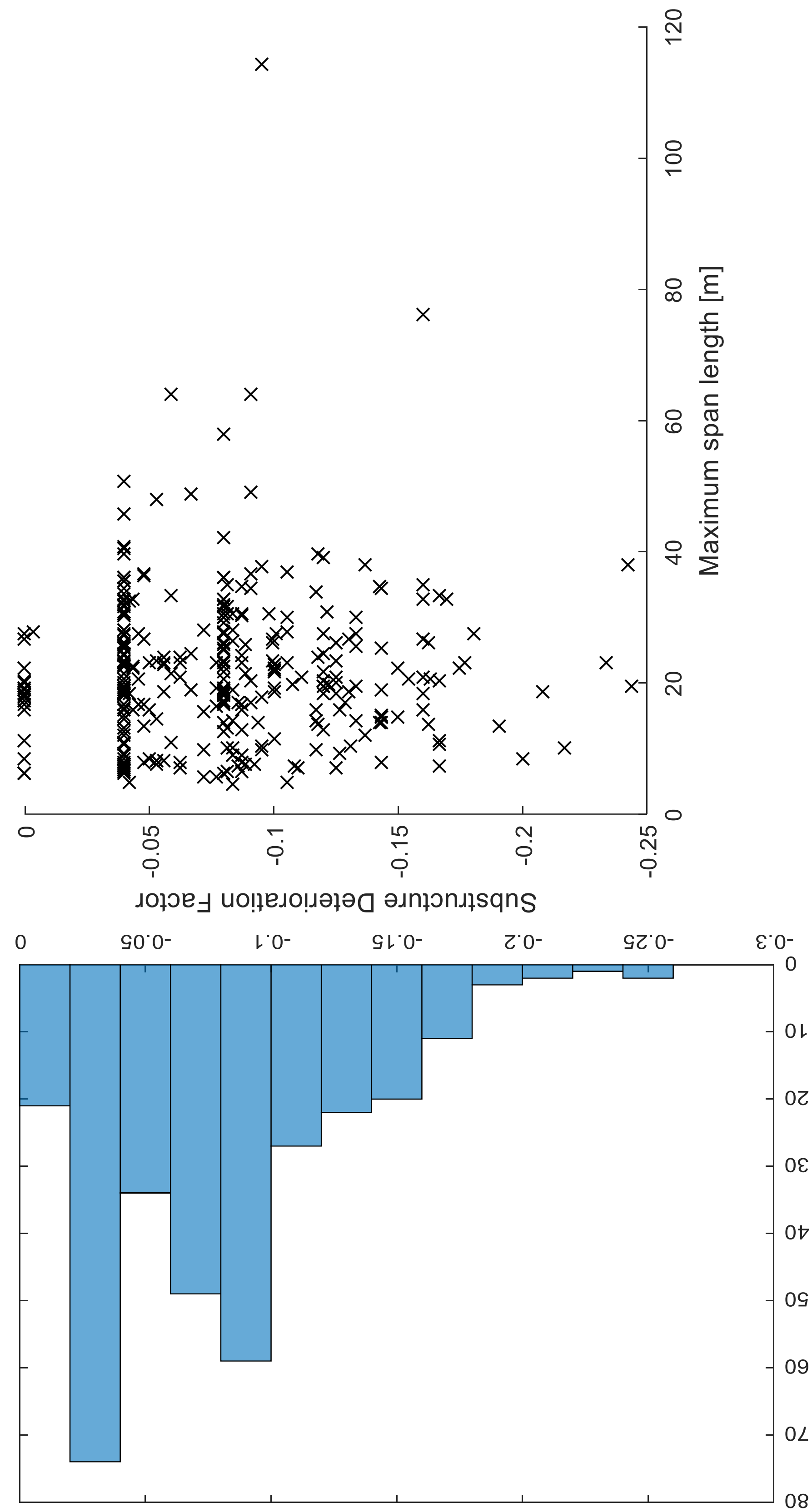
Substructure Deterioration Factor
0
-0.05
-0.1
-0.15
-0.2
-0.25
0 1 2 6 7 8
Service Level



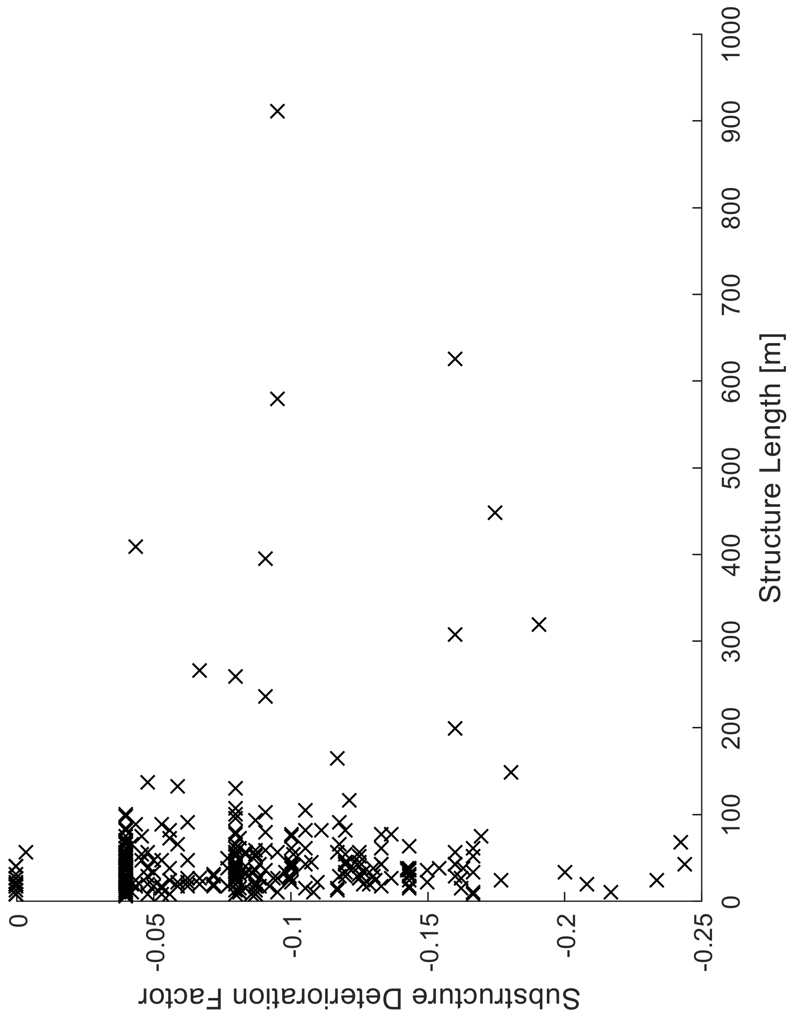
Substructure Deterioration Factor
0
-0.05
-0.1
-0.15
-0.2
-0.25
0 1 2 3 4 5 7
Kind of Material

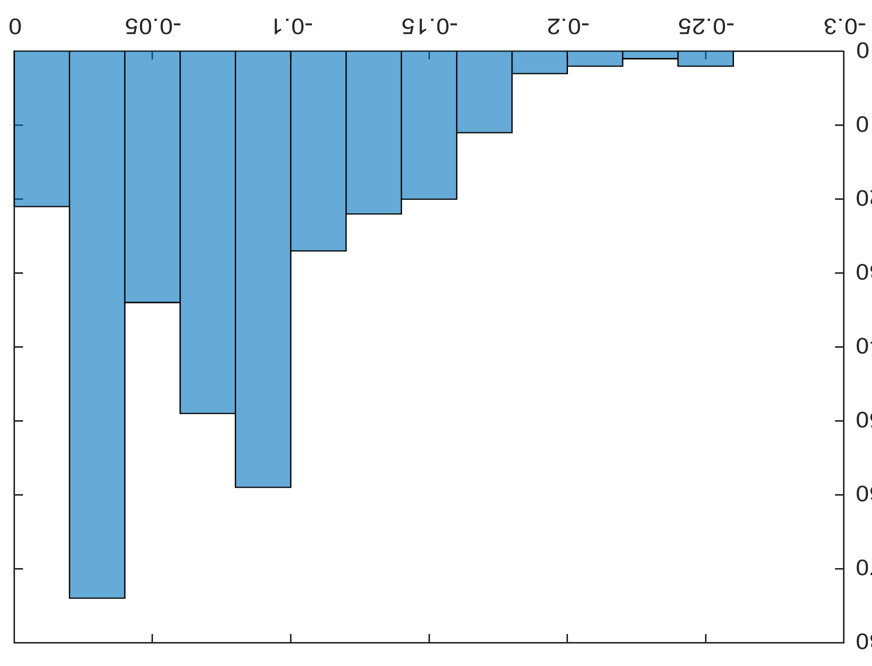

Substructure Deterioration Factor
0
-0.05
-0.1
-0.15
-0.2
-0.25
0
1
2
3
4
5
7
10
11
12
Type of Design


Substructure Deterioration Factor
0
-0.05
-0.1
-0.15
-0.2
-0.25
1
2
3
4
5
6
7
8
Traffic Lanes on structure



Substructure Deterioration Factor
Maximum span length [m]


Structure Length [m]
Substructure Deterioration Factor
0
100
200
300
400
500
600
700
800
900
1000
0
-0.05
-0.1
-0.15
-0.2
-0.25


0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
0
10
20
30
40
50
60
70
80

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