A METHOD FOR PRIORITISATION OF CONCRETE BRIDGE INSPECTIONS IN SOUTH AFRICA

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Dedication

To my Family

Declaration

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Abstract

Bridges are amongst the most important structures of any highway network. Once the bridge construction is complete and a bridge is put into service, it is subjected to deteriorations. An effective condition assessment, as a component of bridge management system, is therefore necessary to keep bridges in admissible conditions of safety and serviceability. In South Africa, some bridge authorities do not have sufficient funds to carry out bridge inspections at required intervals. In the case where bridge authorities have enough funds, a systematic inspection is performed, covering a number of bridges that are not in need of inspection.

Inspection and maintenance for a limited number of bridges randomly chosen may result in an increase of the number of bridges in critical conditions. A bridge inspection prioritisation method that takes into account the need of inspection of bridges is therefore needed for South African highway bridges.

This research provides a prioritisation method for concrete bridge inspections by integration of non-professional inspectors, imagery inspection and deterioration models. To achieve the research objectives of this study, a literature study has been carried out to understand bridge inspection practice in general and South African practice in particular. The literature helped also to identify previous works on bridge inspection prioritisation, the use of information from informal sources, imagery inspection and involvement of non-professionals in bridge inspection and use of deterioration models in bridge management. A survey has been conducted amongst South African bridge authorities in order to fill the literature gaps. Inventory and inspection data of bridges managed by South African National Roads Agency Limited (SANRAL) was used to develop a deterioration model by considering bridge characteristics such as bridge age, number of spans, and bridge type.

Based on the literature review, results of surveys and estimated regression parameters, a bridge inspection prioritisation method has been developed. This method comprises three phases. The first phase is the initial screening that consists of an identification of bridges with critical defects that have not been repaired yet. These bridges, to which are added bridges that have not been inspected in the previous inspection, constitute the first inspection priority category. The second phase is an imagery screening which is an analysis of digital photographs for detection of defects that need urgent assessment by professional inspectors. The analysed photographs are taken by non-professional inspectors and uploaded to the Bridge Management System. The third phase is a grouping of bridges in inspection priority categories as a function of their physical characteristics and deteriorating factors using deterioration modelling.

The method has been applied on SANRAL bridges using inspection ratings of 2011-2012. 422 SANRAL bridges have been categorised in the first inspection priority group by considering hydraulic related defects as critical. The third phase allowed to rank 522 possible combinations of bridges based on their characteristics. The developed method would help bridge authorities where inspection budget is limited, to prioritise bridge inspection as a function of needs of inspection.

Opsomming

Brûe is ŉ belangrike deel van enige snelweg netwerk. Wanneer brugkonstruksie voltooi is en dit in diens gestel word, is die brug onderhewig aan skade en verval . 'n Doeltreffende toestandsassessering, as 'n komponent van ŉ brug bestuurstelsel, is dus nodig om brûe in ŉ toestand van veiligheid en diensbaarheid te hou. In Suid-Afrika het sommige brugowerhede nie genoeg fondse om bruginspeksies teen vereiste intervalle uit te voer nie. In die geval waar ŉ brugowerhede wel genoeg fondse het, word stelselmatige reekse inspeksies uitgevoer, waar brûe wat nie lukraaknoodwendig op daardie stadium inspeksie nodig het nie, ook soms ingesluit word. Inspeksie en onderhoud vir slegs 'n beperkte aantal brûe wat gekies word kan 'n toename veroorsaak in die aantal brûe wat in ŉ kritiese toestand is. 'n Bruginspeksie prioritiseringmetode wat brûe identifiseer vir inspeksie is dus nodig vir Suid-Afrikaanse brugowerhede.

Hierdie navorsing stel 'n metode voor wat bruginspeksies prioritiseer deur gebruik te maak van nie-professionele inspekteurs, inspeksie van foto’s en brugtoestandsvervalmodelle. Om die navorsings doelwitte van hierdie projek te bereik, is 'n literatuurstudie uitgevoer oor die praktyk van bruginspeksie in die algemeen, en meer spesifiek om die praktyk in Suid-Afrika te verstaan.. 'n Opname is voorts onder Suid-Afrikaanse brugowerhede uitgevoer om gapings in die literatuur aan te vul. Inventaris en inspeksie data van brûe wat bestuur word deur die Nasionale Padagentskap (SANRAL) is daarna gebruik om 'n toestand agteruitgangsmodel te ontwikkel deur die eienskappe soos brug ouderdom, aantal spanne en die tipe brug in ag te neem

Gebaseer op die literatuur, resultate van opnames en beraamde regressie parameters is 'n brug inspeksie prioritiseringsmetode ontwikkel. Hierdie metode bestaan uit drie fases. Die eerste fase is die aanvanklike siftingsproses wat bestaan uit die identifisering van brûe met 'n kritiese defek wat nog nie herstel is sedert ŉ vorige inspeksie nie. Hierdie brûe, wat ingesluit word by ander brûe wat nie geïnspekteer was in die vorige inspeksie nie, is die eerste kategorie van inspeksie prioriteit. Die tweede fase is 'n ontleding van digitale foto's vir die opsporing van defekte wat dringende assessering deur professionele inspekteurs nodig het. Die foto's word geneem deur nie-professionele inspekteurs en dit word gelaai op die brug bestuurstelsel. Die derde fase is die groepering van brûe in inspeksie prioriteit kategorieë as 'n funksie van hul fisiese eienskappe en vervalfaktore met die hulp van agteruitgangsmodelle.

Die metode is toegepas op die SANRAL brûe met die hulp van inspeksie graderings van 2011-2012. Deur die aanname van hidrouliese defekte as van kritiese belang, is 422 SANRAL brûe in die eerste inspeksie prioriteit gegroepeer. Die derde fase prioritiseer 522 moontlike kombinasies van brûe op grond van hul fisiese eienskappe. Die metode sal brugowerhede waar inspeksie begrotings beperk is, help om bruginspeksies te prioritiseer as 'n funksie van die noodsaaklikheid van inspeksie.

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List of abbreviations

AADT:	Annual Average Daily Traffic
ADT:	Average Daily Traffic
ASCI:	Average Structure Condition Index
BCI:	Bridge Condition Index
BMS:	Bridge Management System
CI:	Condition Index
CSIR:	Council for Scientific and Industrial Research (South African)
DCR:	Deck Condition Rating
DER:	Degree Extent Relevancy
DFID:	Department for International Development
DOT:	Department Of Transport
D-rating:	Degree rating
ESAL:	Equivalent Single Axle Load
GPS:	Global Positioning System
ID:	Identification number
IIMM:	International Infrastructure Management Manual
IQOA:	Image de la Qualité des Ouvrages d’Art
MLE:	Maximum Likelihood Estimate
N3TC:	N3 Toll Concession
NCHRP:	National Cooperative Highway Research Program (United States of America)
NHS:	National Highway Systems
R:	Coefficient of determination
R-rating:	Relevancy rating
SANRAL:	South African National Road Agency Limited
SPCI:	Structure Priority Condition Index
SSE:	Sum of Square Errors

SST: Total sum of Square Errors

TMH: Technical Methods for Highways

TRAC: Trans African Concessions

UAV: Unmanned Aerial Vehicle

U-rating: Urgency rating

USDOT: United States Department Of Transport

VIF: Variance Inflation Factor

List of variables / symbols

$\hat{y}$ or $Y(t)$: Dependent variable

$\hat{\beta}$: Least square estimator

$\frac{\pi}{1-\pi}$: The odds

$\prod$: Product

$\sum$: Sum

$1-\pi$: Failure probability

Ic: Condition index

Ip: Priority index

L: Least squares function, likelihood function

LR: Likelihood ratio

P: Transition matrix

t: Time

wci: Priority weight for inspection item i

β: Regression parameter

x or X: Independent variable

ε: Regression error

π: Response probability

$Element_{Condition}$: Condition rating of a bridge element

CHAPTER 1. INTRODUCTION

1.1 Background and rationale

Bridges are amongst the most important structures of any highway network. During their service life, bridges are subjected to deterioration that may harm the serviceability and the safety of the bridge. These deteriorations are influenced by many factors such as construction materials and quality of construction, nature and intensity of traffic loadings, environmental factors and maintenance factors (Ryall, 2009). Therefore, detection and repair of bridge deteriorations are required to preserve an acceptable use of highway networks. This is achieved by managing a sound bridge management system which in turn requires a complete inventory of bridges, a regular inspection, a convenient analysis of inspection data and estimate of repair costs, a preparation of maintenance budget and an efficient prioritisation of maintenance operations.

Inspection is among the most important elements of bridge management as it allows to assess the condition of the bridge components from which necessary maintenance activities are determined in order to keep the bridges in admissible conditions of safety and serviceability. Bridge inspection also allows to monitor the effect of change in traffic loads on bridges and the behaviour of strengthening and repair techniques (Ryall, 2009). The above mentioned purposes of bridge inspection prove the necessity of a regular and well-structured bridge inspection in a bridge management system.

In South Africa, the inspection of the complete number of bridges on a regular basis is not possible for many of bridge management institutions because of limited availability of funds allocated to bridge inspection and maintenance which implies a selection of a limited number of bridges to be inspected every 3-5 years (Wium & Rautenbach, 2004). Even where a complete and regular inspection is possible, the bridge inspectors inspect bridges one by one whilst an important number of bridges may still be in the same conditions as the previous inspection.

A random or systematic choice by a bridge authority of the bridges to be inspected does not allow to choose bridges that are the most in need of inspection. Inspection and maintenance for a limited number of bridges chosen therefore result in an increase of the number of bridges in critical conditions after a certain period of time (Wium & Rautenbach, 2004).

The use of a prioritisation method for bridge inspection should help bridge authorities with a limited inspection budget, to categorise bridges according to their inspection needs. Resulting categories will help to prioritise bridge inspection as a function of available funds. The same approach will also allow the bridge authorities with sufficient inspection budget to perform inspection of only bridges in need of inspection. The purpose of this study is to investigate a prioritisation method that combines involvement of non-professional inspectors with imagery based inspection, and deterioration models.

1.2 Research Problem

South African highway bridges are mainly of concrete and are inspected by the South Africa National Roads Agency Limited (SANRAL), Provincial departments of transport and by Municipal transport agencies. A principal inspection is scheduled every 5 years and carried out by experienced inspectors who produce records of defects.

In some bridge authorities, the available inspection funds do not allow to respect the required inspection intervals. For example in the Province of Eastern Cape, for 1382 bridges registered in the official provincial Bridge Management System in 2004, only 1191 bridges were inspected from 1995 to 2003 i.e. in a period of 8 years, and 191 bridges had by then not been inspected yet (Wium & Rautenbach, 2004).

In the case where bridge authorities have enough funds to carry out regular inspections, an exhaustive inspection is performed, covering a number of bridges that are not in need of inspection. This is illustrated by inventory and inspection data of March 2014 obtained from the South African Council for Scientific and Industrial Research (CSIR). Table 1-1 illustrates the changes in Condition Index (CI) for the 777 bridges that have been inspected twice by SANRAL. It has been found that 7.9 % of bridges didn't have any change of condition index at the second inspection and the change in CI is less than 5 (on a scale of 0-100) for 35.6 % of the bridges.

Table 1-1. CI change for bridges that have been inspected twice

	Change in CI between two consecutive inspections			
	No change	Change <= 5	Change > 5	Total
No of bridges	61	277	439	777
%	7.9	35.6	56.5	100.0

From the above situation, the need for a prioritisation method of bridge inspections is identified. Such a prioritisation method will help the bridge authorities where the inspection budget is limited, to choose the bridges which are the most in needs of inspection.

On the other hand, this prioritisation method will help the bridge authorities that have the capacity to inspect all bridges, to adjust the inspection interval according to bridges inspection needs. This will save funds by preventing inspection of bridges that may still be in the same conditions.

1.3 Research objectives

The aim of this work is to provide a prioritisation method for concrete bridge inspections that allows to inspect the most probably deteriorated bridges by involving non-professional inspectors and using imagery inspection and deterioration models.

During this study, the following specific objectives will be achieved:

- To investigate the role of routine maintenance teams in bridge inspection in South Africa
- To develop a deterioration model for South African bridges.

1.4 Research scope

Bridge inspections involve costs depending on the human resources and equipment used. The costs vary as a function of required skills for a particular inspection, required time for inspection and equipment needed.

This research provides a method for prioritisation of bridge inspections and is limited to the identification of the most probable deteriorated bridges. Therefore, the costs involved in either the inspection or the repair are not investigated in this research.

1.5 Outline of the thesis

The thesis is presented as follows:

Chapter 1 presents the background of the study, the research motivation and objectives.

Chapter 2 treats the literature review on concrete inspection by focusing on community involvement, imagery inspection, and deterioration models. This chapter also treats the evaluation of bridge inspection of South African bridges: types, scope and intervals of concrete bridge inspection.

Chapter 3 describes the methodology used to achieve the research objectives. This methodology includes, more specifically, the methods of acquisition and analysis of data used in this research.

Chapter 4 deals with interpretation and presentation of results of a survey conducted amongst bridge authorities.

Chapter 5 provides a statistical regression and interpretation of results of inventory and inspection data of SANRAL bridges

Chapter 6, provides the inspection prioritisation method by integration of non-professional inspectors, imagery inspection, and bridge deterioration models. An application of this is method is done using SANRAL bridges data.

Chapter 7 provides the conclusions as well as recommendations according to obtained results and the objectives of the study.

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

Bridge components deteriorate as a result of traffic usage, accidental impacts, and environmental actions. A thorough monitoring of the state of deterioration is necessary to permit an implementation of maintenance, repair and rehabilitation actions to preserve the acceptable state of bridges in particular and for highway networks in general. This monitoring is done through bridge inspections for which the nature, intervals and frequencies vary according to country, bridge authority, and bridge type. It is with reference to this and the objectives of this study, that this literature review is structured.

The literature review consists of an overview of Bridge Management System (Section 2.2), a review on bridge inspection in general (Section 2.3) and bridge inspection in South Africa in particular (Section 2.4). It also explores the inspection methods combined in this research. These inspection methods are imagery and non-professionals based inspection which are investigated in Sections 2.5. A review on the use of deterioration models in bridge inspection management is carried out in Section 2.6. A review on previous research done on inspection prioritisation is given in Section 2.7 and a conclusion is carried out in Section 2.8.

2.2 Bridge Management System (BMS)

A bridge management system is a mechanism by which tasks are coordinated and implemented in order to care for bridges (Ryall, 2009). These tasks comprise the collection of inventory data, assessment of bridge condition, maintenance activities and allocation of funds.

All the information about the tasks is grouped to form components of the BMS database as shown in Figure 2-1. However, the BMS is not only a collection of information neither only a computer program (Ryall, 2009; McGee, 2002). It should comprise tools that permit interaction between components, it should allow to identify where to spend funds effectively (Nordengen & Roux, 2006). An effective BMS therefore requires, amongst others, an ability to receive updated (new) data about the condition of bridges, condition of bridges after maintenance activities and should capture data of new bridges.

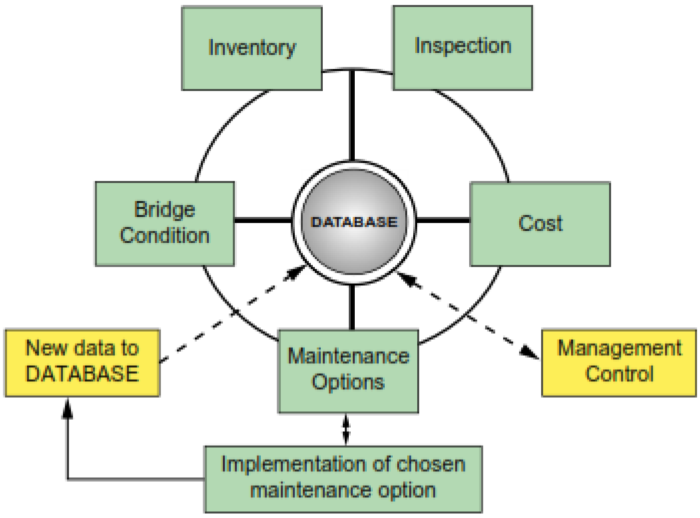


Figure 2-1. A basic BMS (Ryall, 2009)

The inventory provides the starting point of the BMS as it stores basic information about the bridge such as its name, location, construction (date, materials), and information on bridge components. The inspection component stores the information from the inspection reports, which comprises the condition of the bridge, proposed repair activities and their respective priorities, and costs. The maintenance component stores maintenance records which comprise the nature and the cost of the maintenance carried out. The financial component treats the historical information about the costs and can produce regular and reliable financial reports. The bridge condition component uses historical data and inspection information to assign priority for bridge maintenance at network and/or the project levels. The database is basically a store of all the historical and existing information about the bridges. It therefore forms the central part of the BMS.

A bridge inspection is a key element of any BMS as it helps to collect necessary information about the condition of a bridge in the highway system. This helps to establish the condition state of the bridge stock and to determine necessary actions for keeping the bridges in acceptable conditions of safety and serviceability.

2.3 Bridge inspection

The Oxford dictionary (2013) defines a bridge as *"a structure that is built on a road, railway, river, etc. so that people or vehicles can cross from one side to another"*. This definition does not describe a bridge from an engineering point of view because it does not distinguish between many types of structures, such as bridges and culverts for example. TMH 19 (2013) classifies a road structure as a bridge when it fulfils one or more of the following conditions:

- *Any single span (as measured horizontally at the soffit along the road or rail centre line between the faces of its supports) is equal to or greater than 6 m; or*
- *The individual clear spans (as measured horizontally at the soffit along the road or rail centre line between the faces of its supports) exceed 1.5 m and the overall length measured between abutment faces exceeds 20 m; or*
- *The opening height, which is the maximum vertical distance measured from the streambed or structure floor at the inlet or from the top of any base, to the soffit of the superstructure, is equal to or greater than 6 m; or*
- *The total cross-sectional opening is equal to or larger than 36 m; or*
- *The structure is a road-over-rail, or rail-over-road structure, even if the span is less than 6 m.*

The definitions given above are illustrated by Figure 2-2.

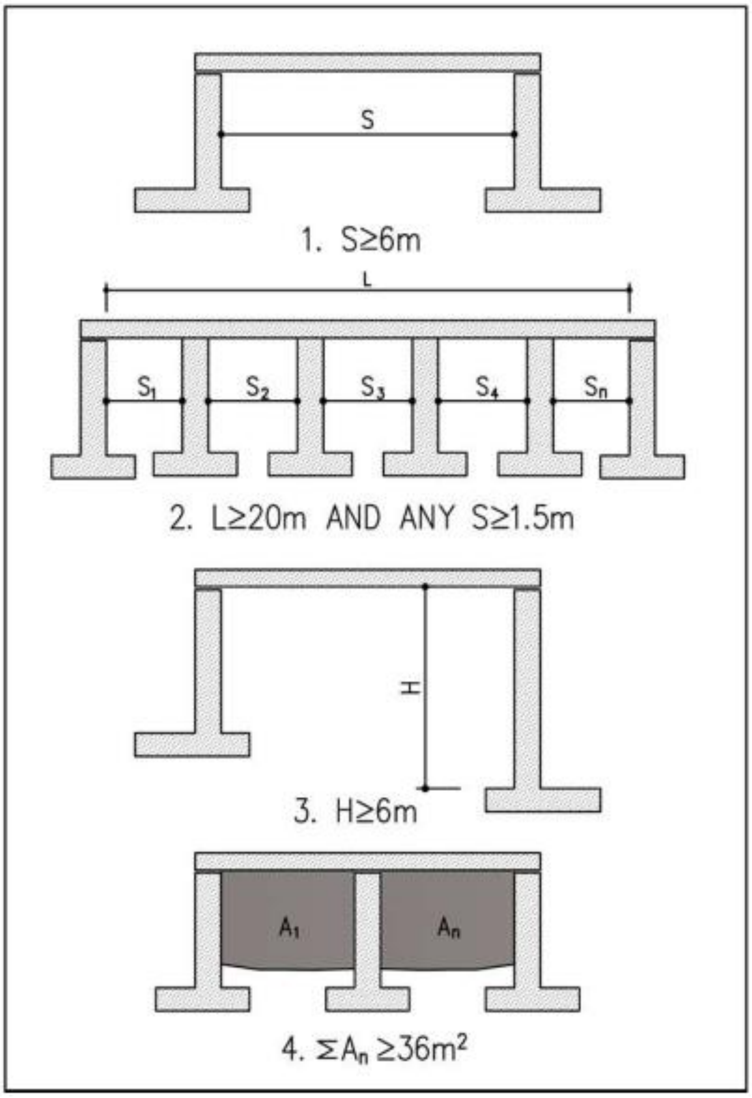


Figure 2-2. Bridge Classification (TMH 19, 2013)

For the purpose of inspection, TMH 19 identify bridge types as:

i. **General bridge** which consists of separate and clearly identifiable elements such as deck slabs, deck expansion joints, abutments, piers and foundation footings and for which roadway is normally a concrete deck.

ii. **Arch Bridge** includes solid spandrel filled arches; open ribbed spandrel arches; and open spandrel arches.

iii. **Cable Bridge** includes suspension bridges; cable stayed bridges and extradosed bridges.

iv. **Cellular Bridge** is a bridge consisting of "cellular" units. Elements such as separate deck slabs, abutments/piers, foundations, etc. are not clearly identifiable while elements such as invert slabs, apron slabs, cut-off walls etc. are normally present.

For the purpose of inspection TMH19 (2013) provides also the bridge items as they are described in Section 2.4.

A bridge inspection is an on-site check of a bridge for defects. The main causes of bridge defects are physical (excessive loading, environment, and accidents), design errors (inadequate cover, errors in calculation, etc.), construction materials (poor quality of materials for example), and construction methods and workmanship (poor mixing of concrete, poor placing of falsework, etc.) (Ryall, 2009). Some of these defects are more critical than others as far as the safety of the bridge users and the structural integrity are taken into account. Investigating bridge failures in United States, Wardhana and Hadipriono (2003) found out that the critical bridge defects that have been the cause of bridge failures or collapses are hydraulic related. These are mainly scour, flood, and debris obstruction. This have also been found also by Davis - McDaniel, Pang, and Chowhury (2013) who used a fault-tree analysis method to identify causal factors of bridge failure and estimate overall failure risk. The application of this method to a segmental box girder bridge in South Carolina, USA, permitted to rank the critical failure factors, from most to least critical, as follows: flood, scour, overloading, corrosion of posttensioning tendons, and earthquake.

Bridge inspections are done to ensure the safety and the serviceability of bridges by detecting their repair needs and for the elaboration of a rehabilitation plan (Hearn, 2007). As for other infrastructure assets, bridge inspection can be done visually and can include the use of measurement and testing tools (IIMM, 2011).

In general, according to its target, inspections vary from frequent and superficial to infrequent and thorough inspection (Hearn et al., 2005). *Superficial inspections* are quick assessments of unusual defects such as new significant defects or damages from accidents, floods or other important actions. *General inspections* are done to evaluate the growth of defects known form the previous inspection and check for the development of the new ones. *Principal inspections* are thorough visual examination of a bridge in order to identify its condition. The names and intervals of these types of inspection vary with countries as shown in Table 2-1.

Intervals between consecutive inspections depend on the focus of the inspection and vary from one country to another and may vary from one institution to another within the same country. Theoretically, the optimal interval between consecutive inspections corresponds to the lowest cost of inspection, repairs/rehabilitations and failures impacts (Tolentino & Ruiz, 2014). In fact, the inspection and repair costs reduce as the inspection interval increases but the failure costs increases with inspection interval as the probability of failure increases with time. Figure 2-3 shows an example of determination of optimal inspection interval which corresponds to the lowest point of the "Total cost" curve.

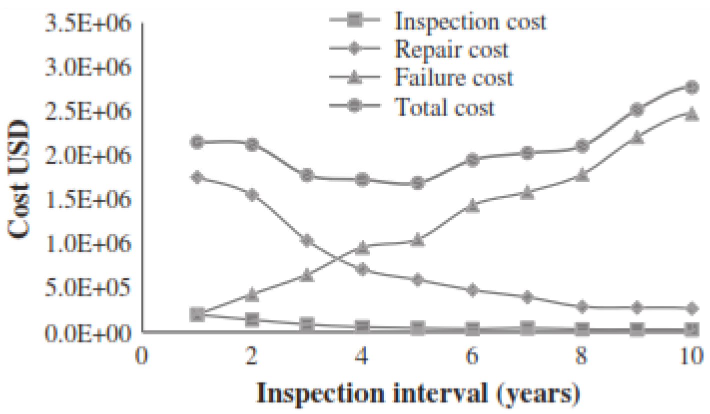


Figure 2-3. Theoretical determination of optimal inspection interval (Tolentino & Ruiz, 2014)

Practically, inspection intervals vary from 1 year for an annual check or routine inspection to 60 months for underwater inspection in United States and principal inspections in South Africa (Hearn, 2007). Inspection intervals may reach 6 years and even more in some other countries such as Denmark, France and Finland for principal inspections (Hearn, 2007). Table 2-1 shows a summary of bridge inspection frequencies in different countries.

The bridge inspection intervals vary from one country to another which is a result of different deteriorating factors in those countries. For example, in countries such USA and Germany where the environment is more severe (effects of freeze-thaw cycles, use of de-icing chemicals, etc.) the inspection intervals will tend to be short as the failure costs increase rapidly.

Table 2-1. Inspection intervals in different countries (Hearn, 2007)

Inspection Interval	U.S.	Denmark	Finland	France	Germany	Norway	South Africa	Sweden	United Kingdom
3 months					Superficial				Superficial
1 year		Routine	Annual	Annual		General	Monitoring	Superficial	
2 year	Routine								General
3 year				IQOA	Minor			General	
4 year	Routine 48-month								
5 year			General 5-year			Major	Principal		
6 year		Principal		Detailed	Major			Major	Principal
7 year									
8 year			General 8-year						
10 year	In-depth 120-month								
For Project	Special	Economic Special	Special		Special	Special	Project-level	Special	Special

IQOA = the Picture of the Quality of Engineering Structures from its French name: Image de la Qualité des Ouvrages d’Art.

During a concrete bridge inspection, most of the defects to be sought are concrete inherent defects such as, concrete carbonation, reinforcement corrosion, concrete spalling and cracks, etc. Other common defects are environment or traffic related defects such as scour, settlement, and defective surface. (Hearn et al., 2005).

A bridge inspection is done by a bridge inspector whose qualification and experience depends on the nature of inspection and the regulations governing inspection in the bridge authority. The bridge inspector may be a technician, a civil engineer or a bridge engineer and must hold a bridge inspection certificate. During inspection, the bridge inspector rates every defect he/she finds at which he/she attributes a score/number that depends on the defect's severity.

The condition rating systems are different form one country to another. For example, the condition rating is 0-to-5 in Denmark while it is 1-to-4 in France (Ryall, 2009). In some countries, the bridge inspector provides supplementary information such as his/her recommendation on repair urgency, effect of defect on the traffic, etc. (Ryall, 2009). The inspection report gives detailed descriptions of defects and comprises also photographs and sketches describing the defects. Table 2-2 gives a summary on rating systems in different countries.

In general, the defects' rating is on a 4-level scale or 5-level scale with some exceptions such as the USA when a 9-level scale is used. The limited number of rating levels provide a detailed description of the bridge defects while minimising the influence of the inspection subjectivity.

In many country rating systems, supplementary information is provided for every defect. This information may be defect relevancy, impact of the defect on the durability of the structure, impact of the defect on the traffic etc. depending on the country. When the rating of supplementary information is used in the calculation of performance indices, it helps to include the consequence of defects on serviceability and safety of bridges.

The performance indices serve as maintenance priority rating as engineering judgement on maintenance is given in supplementary information for example as urgency (South Africa), or time to repair (Norway).

The ratings systems are different from one country to another. In countries such as the USA, a bridge or a bridge component as a whole, is rated without any other supplementary information and it gives a superficial reflection of the condition of a bridge. On the other hand, other countries/bridge owners (South Africa for example) rate defects and give supplementary information such as the consequence of the defect on the bridge serviceability. This helps to monitor the condition of bridges at defect level, and provides an understanding of the rate of deterioration for every defect. However, this method may also result in expensive inspections in terms of collection and management of inspection data.

Table 2-2. Condition rating systems for different countries and inspector's training (Hearn et al., 2005; Hearn, 2007)

Country	Defect rating system	Supplementary information	Inspection team	Inspector training
USA	1 to 9		Team leader	
Denmark	0 to 5	Inspector's recommendation on repair urgency	• Bridge inspectors • Road foreman • Roadman	Mentoring by experienced inspectors
Finland	0 to 4	Importance in load path, severity, urgency of repair, condition of bridge element	• Engineer: Certified bridge inspector Basic • Certified bridge inspector • Road foreman	4-day course, 2-day field tests and annual field testing
France	1 to 3	With intermediate 2E, 3U indicating necessity of urgent action and S for conditions endangering user's safety	• Certified inspector • Inspection agent • Road maintenance agent	Training in 6 modules
Germany	1 to 4	Defect stability, threat to durability and traffic safety	• Bridge inspector • Road maintenance crew	1-week course
Norway	1 to 4	Impact of the defect to loading capacity, traffic capacity, maintenance cost or environment.		
South Africa	0 to 4	In 4 categories: Degree, Extent, Relevancy and Urgency	• Senior bridge inspector • Bridge inspector • Maintenance personnel	Training courses by consultants
Sweden	0 to 3	Rating in 3 categories: physical, economical and functional condition	• Maintenance Contractor • Bridge inspector	SNRA training course
United Kingdom	1 to 5	A to E for extent rating	• Supervising engineer • Bridge inspector	

The inspection teams are led by bridge engineers but may also comprise technicians that have been trained and certified as required by the country's bridge inspection regulations. Table 2-2 gives examples for some countries.

The quality of bridge inspection is important for the efficiency of a bridge inspection system. Bridge authorities perform quality control reviews of inspection reports by verifying that inspection reports are accurate and complete. The quality control aims also to verify whether reports contain sufficient notes, sketches, and photographs of conditions; and that recommendations for maintenance are appropriate (Hearn, 2007). Therefore, every inspection report should meet the quality requirements before it is used in the bridge management decision making.

The following section gives a detailed overview of bridge inspection practice in South African bridge authorities.

2.4 Bridge inspection in South Africa

The South African highway network comprises a large number of bridges of which a high percentage is constructed in concrete i.e. reinforced concrete, prestressed concrete and composite concrete-steel. The inventory and inspection of bridges is done by the South Africa National Roads Agency Limited (SANRAL) for bridges on national roads, 9 Provincial departments of transport for bridges on provincial roads and Municipal transport agencies for bridges on municipal roads (Hearn, 2007). Concessionaires are also involved in the management of some of the bridges situated on national roads.

The collected inspection data and photographs are converted in an electronic format and transferred to the Bridge Management Systems (BMS). These BMS have been developed by The Centre for Scientific and Industrial Research (CSIR) and is used by SANRAL and some cities and authorities such as Cape Town and Spoornet (Ryall, 2009; Nell, Nordengen and Newmark, 2008). Spoornet which became Transnet later abandoned the system because of failure of implementation (Roux, 2015).

South African maintenance practice includes three types of inspections. These are monitoring, principal inspection, and verification inspection (Hearn, 2007).

A monitoring inspection is a quick check on the new defects and the status of the previously known defects. A monitoring inspection is performed by maintenance personnel and it is done at least once a year. During monitoring inspections, monitoring personnel report encountered problems but do not give further details. Monitoring inspections are included in routine maintenance surveys and quick surveys performed after extreme events such floods, accidents, etc. (Hearn, 2007). A monitoring inspection does not produce any condition rating.

A principal inspection is a thorough examination and record of a bridge for all defects. During principal inspection, the effect of defects on the structural integrity of the bridge is reported. This is done by completing an appropriate inspection form and capturing necessary photographs that describe assessed defects. This type of inspection is done by bridge engineers who have experience in bridge design, maintenance, or rehabilitation. Principal inspections should be done every 5 years (Hearn, 2007; TMH19, 2013). The condition data produced during principal inspections are stored in a bridge management database (Hearn et al., 2005; Hearn, 2007).

Verification inspections are annually done for approximately 60 bridges by SANRAL in order to verify accuracy of inspection data (Hearn, 2007).

South Africa has three special types of bridge inspection (TMH19, 2013). These are partial inspections which are carried out on only certain inspection items that require special access equipment, completion inspections conducted on bridges after rehabilitations or completion of new bridges, and waterway inspections conducted by routine maintenance staff once a year on bridges crossing a waterway.

As mentioned above, the principal inspection is the main inspection in the South African inspection practice and the resulting reports and condition ratings form part of the bridge management system. It is for this reason that the word *"inspection"* in the remaining part of this chapter stands for *"principal inspection"*. In the following paragraphs, the process of bridge inspection is explained covering the condition assessment of bridge components to the determination of bridge condition indices.

For the purpose of inspection, a bridge is subdivided into 21 items as shown in Table 2-3 (Hearn, et al., 2005; Nordengen & De Fleuriot, 1998; Nordengen & Nell, 2005). However, bridges are inspected at the level of sub-item. For example, for the item "Piers and columns", the individual piers are sub-items; for the item "Longitudinal members", the longitudinal members on one span are considered as one sub-item (Nordengen & De Fleuriot, 1998).

During an inspection, each sub-item of a bridge is inspected visually and its condition is rated according to its level of defect. The rating of a sub-item is defined as the rating of the defect that the inspector judges the worst. The worst defect usually corresponds to that with the highest relevancy rating (TMH19, 2013). Table 2-4 lists the typical bridge defects.

Table 2-3. Main bridge components (Hearn et al., 2005)

Approach embankment	Surfacing	Bearings
Embankment protection works	Superstructure drainage	Drainage features
Guardrail	Curbs/sidewalks	Expansion joints
Waterway	Parapet/handrail	Longitudinal members
Abutment foundations	Pier protection works	Transverse members
Abutments	Pier foundations	Deck slab
Wing/retaining walls	Piers and columns	Miscellaneous items

Table 2-4. Bridge defects (Hearn et al., 2005)

Spalling	Cracks: bending, shear	Defective surfacing
Scour	Rotating abutments	Excessive deflections
Erosion	Defective drains	Expansion joints not watertight
Settlement	Defective guardrails	Defects on concrete surface
Honeycombing	Insufficient cover of reinforcement	Flood debris accumulation

The defects are rated for their Degree, Extent, and Relevancy (DER) as it is shown in Table 2-5. Typically, the DER system categories are rated in four levers from 0 (no defect) to 4 (critical defect) as it is shown in Table 2-6.

Degree of defect is a visual rating of a defect. It defines the severity of the defect without taking into account the consequence of the defect on the inspected item or the structure as a whole.

Extent of defect indicates how the defect is spread out on the inspected item.

Relevancy of defect defines the importance of the defect in terms of the safety of the user or the structural and functional integrity of the item inspected.

These three aspects help to evaluate defects not only for their severity but also its impact on the structure and its consequences on the safety of the structure's users.

During inspection, the inspector also gives his/her recommendation of the urgency of defects to be repaired.

After inspection, the resulting data are used to determine the condition index where each bridge is given a score that depends on the condition in which each item has been found.

Table 2-5. DER rating system (Hearn et al., 2005)

D: Degree of defect	Severity of defect
E: Extent of defect	Prevalence of the defect within the bridge element
R: Relevancy of defect	Impact of the defect on structural integrity and/or user safety
U: Urgency of defect	Recommend time for repair

Table 2-6. DER Categories' values (Hearn et al., 2005)

	Degree	Extent	Relevancy	Urgency
X	Not applicable			
U	Unable to inspect			
0	No visible defects			Monitor
1	Minor	Local	Minimum	Routine
2	Fair	> Local	Moderate	< 5 years
3	Poor	< General	Major	< 2 years
4	Severe	General	Critical	ASAP

2.4.1 Condition indices

TMH19 defines "Condition Index" as the numerical rating of an asset depending on its structural integrity or condition, measured as a percentage. Using sub-item ratings, indices may be calculated for the inspected bridge. These are Structure Priority Condition Index (SPCI) and Average Structure Condition Index (ASCI) (TMH22, 2013; Nordengen & Nell, 2005).

The SPCI takes only into account the worst rating of the sub-items of an item by "ignoring" best ratings whereas all the ratings are considered when calculating the ASCI (Nordengen & De Fleuriot, 1998). This implies that the SPCI tends to exaggerate the poor condition of an item/bridge. On the other hand, the D, E and R ratings are all used to calculate SPCI whereas R rating is not considered in the determination of ASCI. Therefore, SPCI is the best to rank the bridge maintenance priority as it takes into account relevancy rating-consequence of the defect on the structural integrity and user's safety. ASCI is the best when it comes to have an indication of a condition of a structure as a whole.

The calculation procedures of the indices are described hereafter.

Structure Priority Condition Index (SPCI)

In a newly developed method for road structures (TMH22, 2013), the Structure Priority Condition Index (SPCI) is firstly calculated at the inspection sub-item level. The inspection item level indices are then used to calculate the priority indices at inspection item level which in turn are used to calculate the priority indices for the bridge.

TMH22 (2013) gives the following procedure that is used to determine the bridge priority index:

- *Each inspection item is marked as "Ignore", "Forced" or "Normal";*
- *Inspection items marked as "Ignore" are excluded from the SPCI calculations;*
- *A priority condition index is calculated for each relevant inspection sub-item (an inspection sub-item with a D-rating of 0, 1, 2, 3 or 4) of forced and normal inspection items;*

- *The lowest priority condition index of all the relevant inspection sub-items of forced and normal inspection items are used to determine the lowest category of priority condition indices for normal inspection items that will be used in the calculation of the SPCI;*
- *For normal inspection items, the priority indices for all relevant inspection sub-items falling in the lowest category, determined for all relevant inspection items, are added together and divided by the number of relevant sub-items in the lowest category to obtain the priority condition index for the normal inspection item;*
- *For forced inspection items, the priority condition indices for all relevant inspection sub-items falling in the lowest category determined for that specific inspection item, are added together and divided by the number of relevant sub-items in the lowest category to obtain the priority condition index for the forced inspection item;*
- *The priority index for each normal and forced inspection item is then multiplied by an inspection item weight; and*
- *These weighted inspection item priority indices for all the normal and forced inspection items are then added together and divided by the sum of the weights to arrive at the Priority Index for the structure.*

Inspection sub-item priority index

The priority index of inspection sub-item j of inspection item i, Ip is calculated using the following equation (TMH22, 2013).

$$Ip_{ij} = 100 - \frac{100(k_d \times D + k_e \times E)R^a}{b_p}$$

Where: D = degree rating for inspection sub-item j of item i;

E = extent rating for inspection sub-item j of item i;

R = relevancy rating for inspection sub-item j of item i;

k_d = degree coefficient (tentative default value: 1.0);

k_e = extent coefficient (tentative default value: 0.25);

a = relevancy exponent (tentative default value: 1.5); and

b_p = $(k_d \times D_{max} + k_e \times E_{max})R_{max}^a$

$(4 \times k_d + 4 \times k_e)4^a$

Where D_{max}, E_{max} and R_{max} are respectively the maximum values of the Degree, Extent and Relevancy ratings.

Ip_{ij} ranges from 0 for D = 4 and E = 4, i.e. the worst condition, to 100 for D = 0 (no defect), i.e. the best condition.

Inspection item priority index

The priority index of inspection item i, Ipi is calculated using the following equation (TMH22, 2013):

$$Ip_i = \frac{\sum_{j=1}^{j=n} Ip_{ij}}{n}$$

Where: Ipij = priority index of inspection sub-item j of inspection item i

n = number of relevant inspection sub-items in the lowest category for inspection item i.

Ip ranges from 0, i.e. the worst condition, to 100, i.e. the best condition. If an inspection item has a priority index of 100, it means that there are no defects on any of the relevant sub-items making up the inspection item.

The Structure Priority Condition Index (SPCI) is calculated using the following equation (TMH22, 2013):

$$Ip_i = \frac{\sum_{i=1}^{i=N} \left(Ip_{ij} \times wp_i \right)}{\sum_{i=1}^{i=N} wp_i}$$

Where: Ip_i = priority index of inspection item i

wpi = priority weight for inspection item i

N = number of relevant inspection items

Inspection items with no relevant inspection sub-items are excluded from the calculation of the SPCI.

The inspection item weights (wp_i) for the various structure types, bridge included, can be the same as the wc_i values presented in Table 2-8, or can be changed for the SPCI calculations.

SPCI ranges from 0, i.e. the worst condition, to 100, i.e. the best condition. If a structure has a SPCI of 100, it means that there are no defects on the structure.

Average Structure Condition Index (ASCI)

Finally, Average Condition Index (ASCI) can be calculated based on the inspection ratings defect i.e. Degree, Extent and Relevancy. ASCI is easier to calculate for road structures as shown by the following steps (TMH22, 2013).

- *A condition index is calculated for each relevant inspection sub-item (a sub-item with a D-rating of 0; 1; 2; 3; or 4);*
- *The condition indices for all relevant inspection sub-items making up an inspection item are added together and divided by the number of relevant sub-items to give the condition index for the inspection item;*

The condition index for each inspection item is then multiplied by an inspection item weight; and

- *These weighted inspection item condition indices for all the inspection items are then added together and divided by the sum of the weights to arrive at the Average Structure Condition Index.*

For inspection sub-items with a D-rating of U (unable to inspect) default ratings are used in the calculation of the condition index for the inspection item as shown in Table 2-7.

Table 2-7. Default values of Degree and Extent for calculation of ASCI (TMH22, 2013)

Inspection item	**D**	**E**
Foundations	0	-
All other items	2	2

Inspection sub-item condition index

The condition index of inspection sub-item j of inspection item i, Icij is calculated using the following equation (TMH22, 2013).

$$Ic_{ij} = 100 - \frac{100(D + E)}{b_c}$$

Where: D = degree rating for inspection sub-item j of item i;

E = extent rating for inspection sub-item j of item i;

$b_c = D_{max} + E_{max} = 4 + 4 = 8$

Ic_{ij} ranges from 0 for D = 4 and E = 4, i.e. the worst condition, to 100 for D = 0 (no defect), i.e. the best condition.

Inspection item condition index

The priority index of inspection item i, Ici is calculated using the following equation (TMH22, 2013):

$$Ic_i = \frac{\sum_{j=1}^{j=n} Ic_{ij}}{n}$$

Where: Icij = condition index of inspection sub-item j of inspection item i

n = number of relevant inspection sub-items in inspection item i.

Ic ranges from 0, i.e. the worst condition, to 100, i.e. the best condition. If an inspection item has a priority index of 100, it means that there are no defects on any of the relevant sub-items making up the inspection item.

Average Structure Condition Index (ASCI):

The condition index for the whole structure, Ic, is calculated using the following equation (TMH22, 2013):

$$I_c = \frac{\sum_{i=1}^{i=N}(Ic_{ij} \times wc_i)}{\sum_{i=1}^{i=N} wc_i}$$

Where: Ic_i = priority index of inspection item i

wci = priority weight for inspection item i

N = number of relevant inspection items

Inspection items with no relevant inspection sub-items are excluded from the calculation of the ASCI.

The inspection item weights (wc_i) for the various structure types, bridge included are the same as the wc_i values presented in Table 2-8.

ASCI ranges from 0, i.e. the worst condition, to 100, i.e. the best condition. If a structure has an ASCI of 100, it means that there are no defects on the structure.

Table 2-8. Proposed weight for ASCI calculation for a bridge (General, Arch and Cable)

Inspection Item	**Weight for CI Calculation**
01. Approach Embankment	2
02. Guardrail	1
03. Waterway	1
04. Approach Embankment Protection Works	2
05. Abutment Foundations	4
06. Abutments	4
07. Wing/ Retaining Walls	3
08. Surfacing	1
09. Superstructure Drainage	1
10. Kerbs / Sidewalks	1
11. Parapet	3
12. Pier Protection Works	1
13. Pier Foundations	4
14. Piers, Columns & Arch Springings	5
15. Bearings	3
16. Support Drainage	1
17. Expansion Joints	1
18. Longitudinal Members & Cable Groups	5
19. Transverse Members	5
20. Decks, Slabs & Arches	5
21. Miscellaneous Items	1

The South African inspection practice considers the daily average of traffic by providing the Bridge Condition Index (BCI) which is calculated according to the following formula (Hearn et al., 2005):

$$BCI_n = \frac{\left(\sum_j I_{c_j}\right) ADT_n}{\sum_i ADT_i}$$

Where:

BCI_n is the bridge condition index for structure n;

$\sum_j I_{c_j}$is the sum of condition index values for all relevant defects in structure n;

ADT_n is the average daily traffic for structure n;

$\sum_i ADT_i$ is the sum of values of average daily traffic for all structures in the prioritisation process.

The calculated indices are used to categorise highway structures in descriptive categories of their conditions as is shown in Table 2-9.

In South African inspection practice, the defects are rated by their degree, extent and relevancy and an engineer's recommendation on the repair urgency is given. Based on the sub-item rating, a structure's priority index is calculated which serves to identify bridges with critical defects that should receive urgent attention in terms of maintenance.

Table 2-9. Condition categories in function of condition index (TMH22, 2013)

Condition Category	Index Range	Condition Category Description	Functional Category Description	Colour Code	Structures
Very Good	85 - 100	Asset is still like new and no problems are expected.	Good service levels at all times	Blue	Good 70 – 100 Green
Good	70 – <85	Asset is still in a condition that only requires routine maintenance to retain its condition.	Mostly good service levels with isolated problems occurring at certain times.	Green	
Fair	50 – <70	Some clearly evident deterioration and would benefit from preventative maintenance or requires renewal of isolated areas.	Reasonable service but with intermittent poor service.	Orange	Warning 50 – <70 Orange
Poor	30 – <50	Asset needs significant renewal or rehabilitation to improve its structural integrity	Generally poor service levels with occasional very poor service being provided.	Red	Critical 0 – <50 Red
Very Poor	0 - <30	Asset is in imminent danger of structural failure and requires substantial renewal or upgrading with less than 10% of EUL remaining.	Very poor service levels at most times.	Purple	

The inspection practice investigated in this section has served as base information to conduct a survey amongst the South African bridge authorities in order to evaluate a need of the proposed bridge inspection prioritisation method. It will be also used to calculate condition indices of bridge during the development of bridge deterioration models as it is explained in Section 2.5.

The next section gives a review of the literature about the use of photographs in bridge inspection, and the involvement of community members in infrastructure maintenance.

2.5 Imagery bridge inspection and involvement of community members

2.5.1 Imagery based bridge inspection

In formal bridge inspections, photographs are taken and form part of the inspection report (Ryall, 2009; Hearn, 2007). Photographs are useful for the record of extent and type of damage of concrete bridge components such as parapet damage, cracks and spalling on other components of the bridge, etc. (Ryall, 2009). Besides this traditional use of photographs in bridge inspection, there is an emerging use of photographs in the processing, analysis and quantification of the bridges damage such as cracks. As such an analysis is tedious and subjective for numerous images Hutchinson & Chen (2006) proposed a statistics based procedure that minimises the human intervention in image analysis and that effectively locate damage in structural members. Li, Hi, Ju and Du (2013) have developed a crack inspection method that comprises an image acquisition device and an image processing software to measure the width of cracks by conversion of image pixel to millimetres. Abudayyeh, Batainehb and Abdel-Qader (2004) proposed an imagery inspection framework where images are taken by a remote controlled image acquisition device to be stored in a central database. These images are processed and the cracks characteristics such as width, type, depth and length are deduced.

The defects detection by image processing has also been done in other fields such as building. An unmanned aerial vehicles (UAV) equipped with a digital camera has been used to monitor a building (Eschmann, Kuo, Kuo and Boller, 2012). The taken digital photos have been processed and used to generated façades of the building. But, most importantly, using these photos, cracks in the building wall could be detected. However the image processing software was not accurate enough so that the building’s edges could mistakenly be taken as cracks during the filtering process. Metni & Hamel (2007) present a new control law for UAV that permits quasi-stationary flights above a planar target. Using an on-board camera, images were taken and analysed by bridge inspection experts and the images allowed them to obtain useful information compared to the information obtained from visual inspection. With digital treatment of images, it was possible to detect cracks of the order of 0.1 mm.

Automated defects detection in structures in general and bridges in particular is developing considerably. The process is improving from manual analysis of image, which involves inspector’s subjectivity to automated procedures which can be incorporated in BMS software and which facilitates the image analysis by using inspection images stored in BMS. However, the low accuracy of these methods results in their limitation to be used in bridge management decision making. Abudayyeh et al., (2004) pointed out the difficulty of implementing their method for all bridge components and explained that this implementation is easier for some elements such as the deck than for others such as piers and girders which are critical elements for the safety of bridges. The other limitation for the accuracy of this method in determination of the position of defects. Li, He, Ju, and Du, (2013) suggested an improvement of their system by incorporating an automatic synchronisation of crack's GPS positions of images.

A use of the image processing methods together with the traditional methods of defects detection is therefore required for better results. These methods may be developed to serve as an extension of the actual BMSs rather than replacing them in order to facilitate their implementation (Abudayyeh, et al., 2004).

The use of UAV presents some advantages such as inspection cost reduction in terms of logistics and working hours, no need of closing the traffic and the use of non-destructive techniques (Metni & Hamel, 2007). However, the use of UAV requires personnel with piloting skills (Hallermann & Morgenthal, 2013) and high-tech command equipment.

Although the published research demonstrates considerable advantages for inspection of structures in areas on the structure where access may be difficult, it still requires the need for skilled operators and considerable cost of equipment.

Therefore, the use of this technology in the prioritisation method developed in this research, to reduce cost of inspections, would not be possible, as the method developed here aims to involve non-professional inspectors with limited skills. Much rather, this research aims to use imagery technology where low skilled operators can make a contribution using low level technology (affordable technology).

A survey has been conducted to investigate whether the BMSs used in South African bridge authorities have a capability of processing inspection photographs to detect and measure defects. This helped to determine the requirements of imagery inspection methods in the proposed bridge inspection prioritisation method.

2.5.2 Involvement of non-professional inspectors in bridge inspection

Reports from informal sources are sometimes used in bridge management systems. A survey conducted in US and Canadian Departments of Transport (DOT) showed that reports of bridge problems from external sources are investigated by bridge inspectors (Hearn, 2007). In US DOTs, most of these informal reports are provided by maintenance crews to inspection personnel. The inspection personnel also obtain this information from other sources such as police and the public. The informal information is stored in bridge paper files in some DOTs and even in BMS database in 4 DOTs (Hearn, 2007).

Canadian transport agencies respond to damage reports submitted by maintenance crews, state police, or the public and some of the agencies keep these reports in bridge paper files and sometimes in BMS database (Hearn, 2007).

In South Africa, maintenance crews are involved in the bridge inspection as they conduct bridge monitoring of bridges on road sections they maintain (Hearn, 2007). The quick surveys performed after accidents, floods, cyclones, or other extreme events do not form part of the maintenance crews' scope of work. This shows that the maintenance crews do not cover all the bridges as they access only those under repair and maintenance.

In some developing countries, the communities have been successfully involved in rural road maintenance with assistance of district engineers (DFID, 2008). The district engineers give technical advice and monitor the quality of the work done. This concept may be extended to bridge inspection where the members of local communities may be involved in assessment of the condition of bridges located in certain boundaries of their communities. Some aspects will have to be defined to meet the effectiveness of community participation in bridge inspection in order to preserve the quality of the provided information. These aspects include the benefit and willingness of community member, type of participation in terms of motivation and his/her capacity to conduct inspection (DFID, 2008).

A combination of the maintenance crew and local community members may give an inspection method that can give basic information during planning and prioritisation of bridge inspection. This method can also integrate the use of imagery based inspection involving photographs that are taken and directly uploaded onto the bridge management system.

This concept is developed and integrated in the prioritisation method that is developed in Chapter 6.

The following section treats the use deterioration models in bridge management and highlights the possibility to use deterioration modelling in bridge inspection prioritisation.

2.6 Deterioration models

2.6.1 Background

Bridge deterioration is a complex mechanism that involves various factors such as construction materials and methods, environment, and traffic. Depending on the cause of the defect, deterioration prediction models have been developed. These are for example cracks induced in reinforced concrete structure by steel corrosion (Kim & Frangopol, 2011; Liu & Weyers, 1998; Alonso, Andrade and González,1988). However, the term "deterioration model" in this research will focus on the overall "condition" of the bridge after it has been subjected to deteriorating factors.

Deterioration models are used to predict future conditions of an asset and this plays an important role in the planning and budgeting of maintenance and rehabilitation of assets. Deterioration models can be divided into deterministic models and probabilistic models.

Deterministic models

Deterministic models are categorised in mechanistic, empirical, mechanistic-empirical models, or are based on expert opinion.

Mechanistic models are built from the fundamental knowledge of physical laws that relate the variables (Montgomery & Runger, 2007). Mechanistic models are developed by defining the model structure and the parameters of the model are determined by experiments. Mechanistic models are not used in infrastructure asset deterioration models because the deterioration of infrastructure depends on many factors that such models cannot explain (Ens, 2012).

In engineering, for some problems there is no simple mechanistic model that explains the phenomenon. To overcome this, empirical models are used. Empirical models combine engineering and scientific knowledge to explain a phenomenon but they are not directly developed from theoretical understanding of fundamental mechanisms (Montgomery & Runger, 2007). Empirical models are developed through a regression process relating condition scores to explanatory variables such as age, location, materials, etc. (Ens, 2012).

The most common and simplest deterministic model in the multiple linear regression model. The estimation of the model seeks to fit the equation (Montgomery & Runger, 2007):

$$\hat{y} = \beta_0 + \beta_1 x_1 + \cdots + \beta_k x_k + \varepsilon$$

Where $\hat{y}$ is the dependent variable, $\beta_0, \beta_1, \ldots, \beta_k$are parameters, $x_1, \ldots, x_k$ are independent variables, and ε_i is the error term.

The parameters $\beta_0, \beta_1, \ldots, \beta_k$may be estimated by the method of least squares. Suppose that n > k observations are available for estimation of the model parameters. The observations may be noted as follows:

$$(x_{i1}, x_{i2}, \ldots, x_{ik}, y_i) \qquad i = 1, 2, \ldots, \mathrm{n}$$

For x_{ij}; i denotes the ith observation and j denotes the level of variable.

For all observations to satisfy the model, the least squares function is:

$$L = \sum_{i=1}^{n} \epsilon_i^2 = \sum_{i=1}^{n} \left(y_i - \beta_0 - \sum_{j=1}^{n} \beta_j x_{ij} \right)^2$$

To minimise L, the least squares estimates of b_0, b_1, …, b_k must satisfy (Montgomery & Runger, 2007):

$$\left.\frac{\partial L}{\partial \beta_0}\right|_{\hat{\beta}_0,\hat{\beta}_1,\dots,\hat{\beta}_k} = -2\sum_{i-1}^{n}\left(y_i - \hat{\beta}_0 - \sum_{j=1}^{k}\hat{\beta}_j x_{ij}\right) = 0$$

And

$$\left.\frac{\partial L}{\partial \beta_j}\right|_{\hat{\beta}_0,\hat{\beta}_1,\dots,\hat{\beta}_k} = -2\sum_{i-1}^{n}\left(y_i - \hat{\beta}_0 - \sum_{j=1}^{k}\hat{\beta}_j x_{ij}\right) = 0 \quad j = 1,2,\dots,k$$

The resulting p = k + 1 least square normal equations may be solved using any method appropriate for solving a system of linear equations in order to estimate the regression coefficients β_0, β_1, …, β_k (Montgomery & Runger, 2007). $\hat{\beta}_0, \hat{\beta}_1, \dots, \hat{\beta}_k$ are the least square estimators of the regression coefficients and the solution to the normal equations. The goodnes of fit for determistic models is done by calculating the coefficient of determination, R^2 as explained in Section 2.6.2.4.

Tolliver and Lu (2001) developed a multiple linear deterioration model for bridge substructures that give a good prediction of condition rating for bridges of Northern Plains of United States (States of Iowa, Minnesota, Nebraska, North Dakota, and South Dakota) with age varying from 0 to 65 years. This model included five main factors which are bridge material, bridge design, operating rating classification, average daily traffic, and the state where the bridge is located. The main weakness of multiple linear regression model, as other deterministic models, is that it assumes that condition rating is continuous whereas it is in a discrete scale in most rating systems.

A third-order polynomial model has been used by Tolliver & Lu (2001) for bridges older than 65 years and by Jiang & Sinha (1989 cited in Wang, 2012) to predict the average of condition ratings for a certain number of bridges.

$$Y_i(t) = \beta_0 + \beta_1 t_i + \beta_2 {t_i}^2 + \beta_3 {t_i}^3 + \varepsilon_i$$

Where $Y_i(t)$ is the condition rating of a bridge at age t, t_i is the bridge age, ε_i is the error term, β_1, β_2, and β_3 are regression parameters and β_0 the recorded condition rating of a new bridge.

Through statistical analysis the following are some of regression equations that have been developed for bridges in the State of Indiana in the USA (Jiang & Sinha, 1989 cited in Jiang, 2010).

- Superstructure condition of concrete bridges on non-interstate highways:

$$Y_i(t) = 9 - 0.29095931 t_i + 0.00860726\, {t_i}^2 - 0.00008815\, {t_i}^3$$

- Substructure condition of concrete bridges on interstate highways:

$$Y_i(t) = 9 - 0.34508455\ t_i + 0.01575857\ {t_i}^2 - 0.00026681\ {t_i}^3$$

Kepaptsoglou and Sinha, 2002 (cited in Sinha et al., 2009) used the following mathematical formula to develop deterioration models for wearing surface, deck, superstructure, and substructure of bridges for Indiana State in the United States.

$$Element_{Condition} = E - \frac{A}{B + C * (Age)^D}$$

Where *Age* represents the number of years since the element was replaced and A, B, C, D and E are coefficients that dictate the shape of the curve. These coefficients have been determined by statistical analysis.

The following are examples of deterioration curves for decks of concrete bridges for Indiana State in United States (Sinha et al., 2009).

$$NHS\ and\ Non - NHS\ Major{:}\ DCR = 3.588 - \frac{133.641}{27.399 + 0.000128 \times year^{3.322}}\ R^2 = 0.99$$

$$Non - NHS\ Minor\ and\ Local{:}\ DCR = 4.702 - \frac{132.844}{35.202 + 0.000009 \times year^{4.040}}\ R^2 = 0.99$$

Where NHS (National Highway Systems), Non-NHS Major, Non-NHS Minor, Non-NHS Local are road classes and DCR is Deck Condition Rating.

Deterministic models are easily understood and used by bridge engineers and managers but present some limitations such as the fact that they cannot be used to derive condition rating of individual bridges and they do not take into consideration the uncertainties of bridge deterioration (Ens, 2012).

Stochastic models

Stochastic models take in account the uncertainties in asset's deterioration. The most popular of the stochastic models is the Markov chain based models. Markov models give the probability, p_{ij}, that an element in state i at time-step t, will be in state j at time-step (t+1). These transition probabilities are assembled in the form of a transition matrix (Wang, 2012).

$$P^{t,t+1} = P(X_{t+1} = j | X_t = i) = \begin{bmatrix} p_{11} & \cdots & p_{1j} \\ \vdots & \ddots & \vdots \\ p_{i1} & \cdots & p_{ij} \end{bmatrix}$$

Where $p_{ij} \geq 0;\ i, j \geq 1;\ \sum_{k-1}^{j} p_{i,k} = 1$.

The following is an example of a transition matrix for deck conditions of concrete bridges on non-interstate highways (Jiang & Sinha, 1989 cited in Jiang, 2010).

$$P = \begin{bmatrix} 0.700 & 0.300 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 \\ 0.000 & 0.780 & 0.220 & 0.000 & 0.000 & 0.000 & 0.000 \\ 0.000 & 0.000 & 0.874 & 0.126 & 0.000 & 0.000 & 0.000 \\ 0.000 & 0.000 & 0.000 & 0.600 & 0.400 & 0.000 & 0.000 \\ 0.000 & 0.000 & 0.000 & 0.000 & 0.500 & 0.500 & 0.000 \\ 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.400 & 0.600 \\ 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 1.000 \end{bmatrix}$$

Logistic regression model is a stochastic model that has also find application in infrastructure deterioration modelling. These are used to determine a probability that a structure is in a particular condition given a set of independent variables. The probability is written in terms of a logistic function as follows:

$$\pi(X) = \frac{e^{\beta_0+\beta_1 X_1+\beta_2 X_2+\cdots+\beta_\mathrm{k} X_k}}{1+e^{\beta_0+\beta_1 X_1+\beta_2 X_2+\cdots+\beta_\mathrm{k} X_k}}$$

Where π represents the response probability; β_0 = constant and β_1, β_2, … are regression coefficients for the variables X_1, X_2, …

The equation above can be written as follows:

$$\frac{\pi}{1-\pi} = e^{\beta_0+\beta_1 X_1+\beta_2 X_2+\cdots} = e^{\beta_0}\left(e^{\beta_1}\right)^{X_1}\left(e^{\beta_2}\right)^{X_2}\ldots$$

Where the ratio $\frac{\pi}{1-\pi}$ is called the odds which is the probability of success π divided by the probability of failure $1-\pi$ (Kutner, et al., 2005).

The regression coefficients are determined by maximising the likelihood function L.

For the observation i;

$$\pi_i(X) = \frac{e^{\beta_0+\beta_\mathrm{i1} X_\mathrm{i1}+\beta_\mathrm{i2} X_\mathrm{i2}+\cdots+\beta_\mathrm{ik} X_{ik}}}{1+e^{\beta_0+\beta_\mathrm{i1} X_\mathrm{i1}+\beta_\mathrm{i2} X_\mathrm{i2}+\cdots+\beta_\mathrm{ik} X_{ik}}}$$

The likelihood function for n observations is:

$$L = \prod_{i=1}^{n} \pi_i(X)^{\sum_{i=1}^{n} Y_i}\,(1-\pi_i(X))^{n-\sum_{i=1}^{n} Y_i}$$

Where $Y_i = 1$ indicates that an event occurs for the ith subject, otherwise, $Y_i = 0$.

It is common to use a numerical algorithm, such as the Newton-Raphson algorithm, to obtain the estimates of the regression coefficients (Kutner, et al., 2005).

The independent variables are the powers of constants and will therefore have a multiplicative effect on the odds. This thus gives the simplest way to interpret the effect of one variable on the likelihood of success when the other variables are considered fixed. For example, when X_1 increases by 10 units, the estimated odds increases by $\left(e^{\beta_1}\right)^{10}$ times.

The goodness of fit may be test by likelihood ratio test which is the ratio of the likelihood at the hypothesized parameter values to the likelihood of the data at the maximum likelihood estimate (MLE (s)). The likelihood ratio (LR) test statistic is given by

$$LR = -2\log\left(\frac{L_0}{L\ at\ MLE\ (s)}\right)$$

Where L_0 is the maximum value of the likelihood when the parameters are restricted based on the assumption. Let assume that L_0 has k less parameters than $L\ at\ MLE\ (s)$.

The assumption is rejected when LR is larger than a Chi-Square percentile with k degrees of freedom. The percentile corresponds to the confidence level chosen by the analyst (Natrella, 2010).

Ariaratnam, El-Assaly, and Yang (2001) used a logistic regression model to set out a method of evaluation of inspection needs for scheduled inspection. This method has been applied on the sewer system of Edmonton, Canada. In this method, the condition rating scale has been divided in two parties: a deficient and non-deficient state. The condition rating which is 1 (best) to 5 (worst) for Edmonton, condition ratings 4 and 5 were considered as requiring repair actions and were thus considered as deficient and condition ratings from 1 to 3 were considered as acceptable and the corresponding sewers were considered as non-deficient. The authors conclude that the method can be used on other infrastructure systems such as bridges provided that the factors contributing to deterioration, deficient state and historical inspection records are known.

Using inspection data of National Bridge Inventory, USA, Brint & Black (2014) concluded that the ordinal logistic regression is the best approach for deterioration modelling. However, these authors found that a linear regression based method is better when the implementation of Ordinal logistic regression is not worth or requires more statistical software.

Other stochastic models that have been developed in bridges deterioration prediction include a bayesian approach, and a semi-markov model (Wang, 2012; Ens, 2012). A semi-markov model is time-dependent, which means that the probability of deteriorating from a state to the next one increases with the age.

The advantages of stochastic models include their use to predict future condition rates based on current ones and reflect uncertainties of bridge deterioration hence these models may be incorporated in risk models (Ens, 2012; Wang, 2012). The major disadvantage of stochastic models is their difficulty to incorporate inspection and monitoring data (Ens, 2012; Wang, 2012).

Based on advantages and disadvantages of the models explained above and the objective of the model to be developed, a choice of the suitable model (s) type can be done. The following section explains the process of deterioration model development in which a suitable deterioration model type is chosen.

2.6.2 Development of deterioration models

Deterioration models are used to describe the condition of a network of bridges as a function of bridge age. The deterioration of bridges is influenced by many factors such as: environment, traffic, materials and methods of construction, and quality of construction and workmanship. To well describe the deterioration of a bridge, a deterioration model will have to consider all these influencing factors.

After data has been collected and mined, the deterioration model may be developed. Adapted from Ens (2012) and Agrawal, Kawaguchi and Chen (2009) the following is a procedure that can be used to develop a deterioration model. This procedure is used to develop a deterioration model in Chapter 5:

- data compilation,
- data mining,
- model type selection,
- development of the model,
- evaluation of the model, and
- testing of the model.

These steps are explained hereafter.

2.6.2.1 Data compilation

To develop a deterioration model, a collection of sufficient and relevant data is necessary. This data has to be collected randomly and has to be representative of the population (NCHRP, 2011).

Bridge deterioration models may be developed from existing inventory and historical inspection data when these are available. The possible data sources are inspection data (condition, individual distresses), asset inventory (material, size, location, functional class, drainage information, slope), traffic data (present or forecasted AADT (Annual Average Daily Traffic), (ESAL (Equivalent Single Axle Load)), maintenance records (applied treatment(s), age), etc. (Ens, 2012)

For these sources of data, there are some advantages and disadvantages involved as far as deterioration model development is concerned. For example, the existing inspection data has the advantage that it may be available for a sufficient period of time and it permits to save time and money for collection. On the other hand, this data may present some disadvantages such as presence of duplicated records and missing information such as maintenance records.

2.6.2.2 Data mining

Before data are used, a data filtering is performed in order to eliminate inspection data affected by rehabilitation, duplicated records, inspector's subjectivity, abnormal sudden drops in ratings, miscoding of inspection ratings etc. Agrawal et al. (2009) developed algorithms used to condition records that seem to be affected by rehabilitation or inspector's subjectivity. For example, a bridge element for which the rating was two points improved to 7 (7 means the element is in new condition = no deterioration) was considered as new and the inspection data before improvement was discarded.

Depending on the objective of the deterioration model, the dependent variable is selected. For example when the model is intended to predict the conditions rating of bridges/components according to their age, the dependent variable will be "the condition rating of bridge/component".

However, the condition rating from inspections may be converted from one system to another in order to allow a better description of dependent variable. Ens (2012) converted the "Original Structural Adequacy Score" with a range of 0-20 into a "New Structural Adequacy Category" ranging from 1 to 7 for the development of a pavement deterioration model for City of Oshawa in Ontario, Canada. This has been done so that the developed deterioration model could be used in conjunction with the City's asset management software.

After the selection of a dependent variable, independent variable(s) are identified. These variables correspond to the factors that significantly influence the dependent variables. When modelling bridge condition rating as a function of its age, the influencing factors include the age, traffic loading, climatic effects (bridge geographic location), freeze-thaw cycles; material type and design type.

To include the dependent variables in the bridge deterioration models, the bridges may be classified into categories that reflect the variables. Sinha et al. (2009) categorised bridges as a function of classes of road they are on and the element materials (steel, concrete) when developing deterioration models for bridge elements (Wearing Surface, Deck, Superstructure) for Indian State, United States. Based on the assumption that the deterioration rate of bridge substructures and arch elements do not depend on the superstructure type or the road class, their deterioration models didn't consider road classes.

Tolliver & Lu (2001) developed a polynomial regression model with good statistical properties and a relatively low coefficient of variation considering the bridge age as the independent variable. For this model, the authors used inspection data from States of Iowa, Minnesota, Nebraska, North Dakota, and South Dakota in the United States. Five main effects on the bridge deterioration have been considered through the development of the model and have been shown to influence the intercept of the deterioration curves. Those effects are: bridge material, bridge design, operating rating classification, average daily traffic, and the state where the bridge is located.

To determine whether there is any relationship between two variables, the correlation between variables is calculated. In the case of a high correlation, the two variables are closely related i.e. as one variable changes, the other changes proportionally. In the other extreme, the two variables change randomly i.e. they are not associated. This is the case of a very low correlation. The correlation between variables may be measured using different measures depending on the scale of measurement of variables involved. Table 2-10 provides the measures of correlation used for interval, ordinal, nominal and dichotomous variables (Ens, 2012).

Table 2-10. Measures of correlation (Ens, 2012)

	Interval	**Ordinal**	**Nominal**	**Dichotomous**
Interval	Pearson correlation coefficient (r^2)	Spearmann's ρ or Kendall's τ*	η (eta)***	point biserial
Ordinal	Spearmann's ρ or Kendall's τ*	Spearmann's ρ or Kendall's τ	Contingency coefficient, Cramer's V**	rank biserial (somer's D)
Nominal	η (eta)***	Contingency coefficient, Cramer's V**	Contingency coefficient, Cramer's V	Contingency coefficient, Cramer's V
Dichotomous	point biserial	rank biserial (somer's D)	Contingency coefficient, Cramer's V	φ (phi)

* interval variable treated as ordinal
** ordinal variable treated as categorical
*** asymmetric measure

Another efficient method to evaluate correlation between variables is the use of Variance Inflation Factor (VIF) (Kutner, et al., 2005). This is done by regressing each independent variable on the remaining ones. For a multiple linear regression model with p variables, VIF for a given independent X_k variable is calculated as follows:

$$(VIF)_k = \frac{1}{1 - R_k^2}$$

Where $k = 1, 2, \dots, p-1$ and R_k^2 is the coefficient of multiple determination when the independent variable X_k is regressed on the p-2 other X variables in the model.

For $R_k^2 = 0$ i.e. there is no linear relation between X_k and other independent variables, $(VIF)_k$ is equal to 1. When $R_k^2 \neq 0$, then $(VIF)_k$ is greater than 1, indicating how much the variance for the regression parameter associated to X_k is inflated by the intercorrelations among the X variables.

The VIF is therefore used as an indicator of the severity of multicollineality. Kutner, Nachtsheim, Neter, and Li (2005) propose a VIF larger than 10 as an indication of serious multicollineality problems that may influence the regression parameters estimates. Some other authors consider 10 as too large and suggest that VIF should not exceed 4 or 5 (Montgomery & Runger, 2007). One of the correlating variables is removed from the model in order to improve the model. The choice of the variables is done based on the scientific or practical reasons. For example, the variable for which measurements are difficult to take are removed before the others. However the removal of such variables may not be beneficial as it may lead to the loss of valuable information contained in deleted variables (Montgomery & Runger, 2007).

2.6.2.3 Model type selection

The modelling technique is chosen among model types as explained above. The chosen model type has to be the best to describe the dependent variable. The discrete dependent variables are well described by Markov models whereas continuous dependent variables are suitable to regression models (NCHRP, 2011).

The amount of available data is also a key factor in the choice of the model type. Indeed the software based models require a large amount of data which means that they are not appropriate when the available data is limited in number. This is also applied to regression models where a large amount of data is needed to estimate the models' parameters (Wang, 2012). The manner in which the model is intended to be used also influences the model type to be chosen. For example, when inspection and monitoring data has to be integrated directly in the model, Markov models are not appropriate (Wang, 2012).

The chosen deterioration model type should be easy to use and understand and its choice also should depend on the manner in which the model will be used after its development. For example, a stochastic model is suitable when the deterioration model is used in making risk based decisions (Ens, 2012).

2.6.2.4 Model development

In order to find the form of model that suits the data the best, a change of various aspects of the model such as the base equation, y-intercept and set of independent variables may be done. Determination of the relationship between identified dependent and explanatory variables is done. This is done by determining the values of parameters that are associated with the variables. In the case of simple regression, least squares method may be used where the values of parameters may be optimised manually using a spreadsheet program such as MS Excel ®.

2.6.2.5 Model evaluation

After it has been developed, the model has to be evaluated. If the model is not judged to be acceptable, the model type should be reconsidered. If the model type is found to be inappropriate, the model form should be changed and the model should be redeveloped. If the evaluation of the model proves that the model is not appropriate to the available data, a different model type should be considered (Ens, 2012).

Statistical measures are performed to check whether model parameters are reasonable and significant. A significant parameter value means that the corresponding independent variable explains a significant variation in the dependent variable while taking into account the presence of the other independent variables in the model. The parameter significance is measured as a p-value on a scale of 0 to 1, and/or is shown as a confidence interval. In general, the parameter is significant for a low p-value (less than 0.05 or 0.01), and a relatively small confidence interval.

For predictive models, an evaluation is done by plotting the residuals i.e. the difference between the value of the dependent variable and the predicted value, over the dependent variable. If the residuals have similar values across the dependent variable, the model is said to be homoscedastic. If residuals are not homoscedastic, the model is better at predicting over certain intervals of the dependent variable.

An important statistical measure when evaluating a model is the coefficient of determination, R^2. R^2 is a measure of how the model fits the actual data and can be calculated in different ways depending on the type of the model. In most cases, R^2 ranges from 0 to 1. Zero means a very poor fit, and 1 means a perfect fit.

For deterministic models, R^2 is calculated as:

$$R^2 = 1 - \frac{\mathrm{SSE}}{\mathrm{SST}}$$

$$SSE = \sum_{i}^{n} (Actual_i - Predicted_i)^2$$

$$SST = \sum_{i}^{n} (Actual_i - Mean)^2$$

Where: *SSE* represents the sum of square errors;

SST represents the total sum of square errors referred to the mean value;

i represents each individual observation;

n represents the total number of observations.

A parameter value is evaluated to be reasonable or not based on prior knowledge. For example, it would not be reasonable that a parameter value associated with age is positive. This is because condition decreases as age increases.

2.6.2.6 Model test

At this final step, the model is verified to be suitable to the purpose of its development. This can be done by ensuring that the model works within the overall asset management system and that it performs as expected in critical ranges.

If the model test leads to the conclusion that it is inappropriate for available data, the model type should be reconsidered and a new model be developed.

The different deterioration models may be developed for given bridges for different purposes such as deterioration prediction, inspection planning, etc. However, it is important to choose the suitable model type and form depending on the intended purpose. The determination of dependent variable and the independent variables is also determinant in the development of a deterioration model. Through the model development process, the parameter values permit to check for significance and reasonableness of associated variables.

The polynomial regression models has been developed for bridges in USA where the age of bridges was the dependent variable and some independent variables such as bridge material, bridge design, operating rating classification, average daily traffic, and bridge location have been found to be significant.

Stochastic deterioration models have been developed but their development requires a use (or development) of advanced software.

The previous sections of this chapter dealt with bridge inspection form a general point of view and in the South African context in particular for which the result is bridge condition rating for every inspected bridge element. The condition rating of items is used to determine bridge condition indices. The bridge condition rating may be predicted as a function of bridge age through the use of deterioration models. The following section consists of a review of literature on the prioritisation of bridge inspection by using the above concepts.

2.7 Inspection prioritisation

The objectives of a regular inspection include, amongst others the provision of a consistent structural state of the bridge. Such inspection helps to understand the structural and material behaviour (Ryall, 2009). However, the use of durable materials and modern bridge construction technology led to construction of more durable bridges that resist more deterioration during the early stages of their service life (Alampalli, William and Healy, 2009). These authors conclude that a 50 year old bridge should not be inspected at the same intervals as a newly constructed one.

On the other hand, bridge monitoring provides important factors that influence the deterioration mechanisms and structural behaviour of bridges which in turn help to eventually adjust deterioration rates assumed at the design stage (Brito & Branco, 1998).

The above mentioned reasons show the necessity of a prioritisation method that combines many sources of information in order to choose the right bridge in need of inspection when the inspection budget is limited. This method would also avoid spending money by inspecting a bridge that is in the same condition as during the previous inspection.

Researches are currently being conducted in USA on the appropriate methods of inspection practices for bridges (Reising & Connor, 2013; Washer, 2013). These methods involve the consideration of many factors such as structure type, age, condition, importance, environment, loading, prior problems, and other characteristics of the bridge to prioritise the inspection of bridges.

Washer (2013) is developing a methodology based on an engineering assessment of inspection needs that can be used in prioritising bridge inspection by determining appropriate inspection intervals, and identify effective inspection strategies. The resulting inspection method is intended to substitute uniform and calendar based bridge inspection and even some new inspection methods that are complicated, expensive and time consuming.

Reising and Connor (2013) incorporated reliability theory and expert judgement to rationally determine bridge inspection needs. This method has been applied on a sample of Indiana (USA) bridges and inspection interval of about 60 % of bridges has been extended during certain time of their lifecycle. Depending on the bridge categories defined according to similarity of design, condition, and loading attributes in the risk process, the extension of inspection interval of 20% of Indiana bridges may vary from 48 to 72 months.

McGeehan and Samuel (1993) studied a prioritisation of bridge underwater inspection based on previous inspection history. The analysis of these authors showed little correlation between bridge age and bridge condition so that they concluded that an older bridge should not necessarily be inspected first. For uninspected bridges, the authors proposed a prioritisation in the following order: concrete structures with spread footings, timber structures and then structures with concrete piles. In each of these categories, the proposed order of priority is: oldest first, structures with high traffic volume before those with lower volume and finally interstate structures before primary and primary before secondary. With all bridges inspected, a different prioritisation system has been proposed where a five-year interval is applied to bridges with high condition rating and a six-month to one year interval for bridges with lower ratings.

2.8 Conclusion

Bridge inspection is a key element of any bridge management system and helps to collect necessary information about the condition of any bridge in the highway system. The bridge inspection practices vary from one country to another and is performed by certified inspectors at fixed interval which is 5 years for principal inspection in South Africa. The defects are rated by their degree, extent and relevancy and an engineer's recommendation on the repair urgency is given.

Based on the sub-item rating, a structure's priority index is calculated which serves to identify bridges with critical defects that should receive urgent attention in terms of maintenance and repair. In the calculation of condition indices, different priority weights are applied to each inspection item which reflect the criticality of different bridge components in terms of risk (the likelihood of occurrence and the impact on the bridge condition) that its condition has on the bridge as a whole. Average Structure Condition Index (ASCI) has been found to be the best to present the condition of a bridge as whole and is thus chosen to be used in the development of deterioration models as these are developed to describe the deterioration of bridge i.e. not the deterioration of components.

The inventory and inspection data stored in a Bridge Management Systems (BMS) can be used to develop bridge deterioration models of given bridges for different purposes such as deterioration prediction and inspection planning. The literature review dealt with the theoretical and practical background of collection and use of data i.e. visual and imagery inspection, and involvement of non-professional inspectors. This background is based on in the conception of the methodology used in this research. The deterioration model developed in Chapter 5 uses the method explained in Section 2.6.

On the other hand, research on the appropriate methods of inspection practices for bridges are being conducted in USA. These includes methodologies that are based on an engineering assessment of inspection needs, reliability theory and risk based methods to determine bridge inspection needs and bridge inspection prioritisation based on previous inspection history. These methods permit a bridge inspection prioritisation that establishes inspection intervals as a function of bridges' needs of inspection. The implementation of these methods would help to reduce time and money spent on bridge inspection while improving the safety and serviceability of highway network.

A bridge prioritisation method is needed for the South African highway network as budgets allocated to infrastructure asset management in general and bridges management in particular are limited. The same prioritisation methods as those in development in USA may be developed for South Africa. However, these method don't suit the case where availability of qualified personnel and records of previous inspections are still a problem as it is shown by the survey that was conducted in South

African bridge authorities for which the results are presented in Chapter 4. Therefore, the bridge inspection prioritisation method developed in this study take into account this issue by combining collection of data by imagery inspection and the development of deterioration models by using available inspection records.

The following chapter describes the methods used to achieve the objectives of this research.

CHAPTER 3. Methodology

3.1 Introduction

The purpose of this study is to develop a bridge inspection prioritisation method that involves non-professional inspectors, imagery based inspection and deterioration models. This method will help to inspect bridges in function of their need of inspection.

During this study, an investigation of the current practice of bridge inspection in some bridge authorities in South Africa has been conducted and an adjustment of bridge inspection intervals was planned to be proposed by identifying the cases in which bridge inspection intervals may be reduced or increased.

This chapter describes the methodology used to achieve the research objectives. The methodology includes, more specifically, the methods of acquisition and analysis of data used in context of this research.

The research methodology, as illustrated by Figure 3-1, is explained in this chapter.

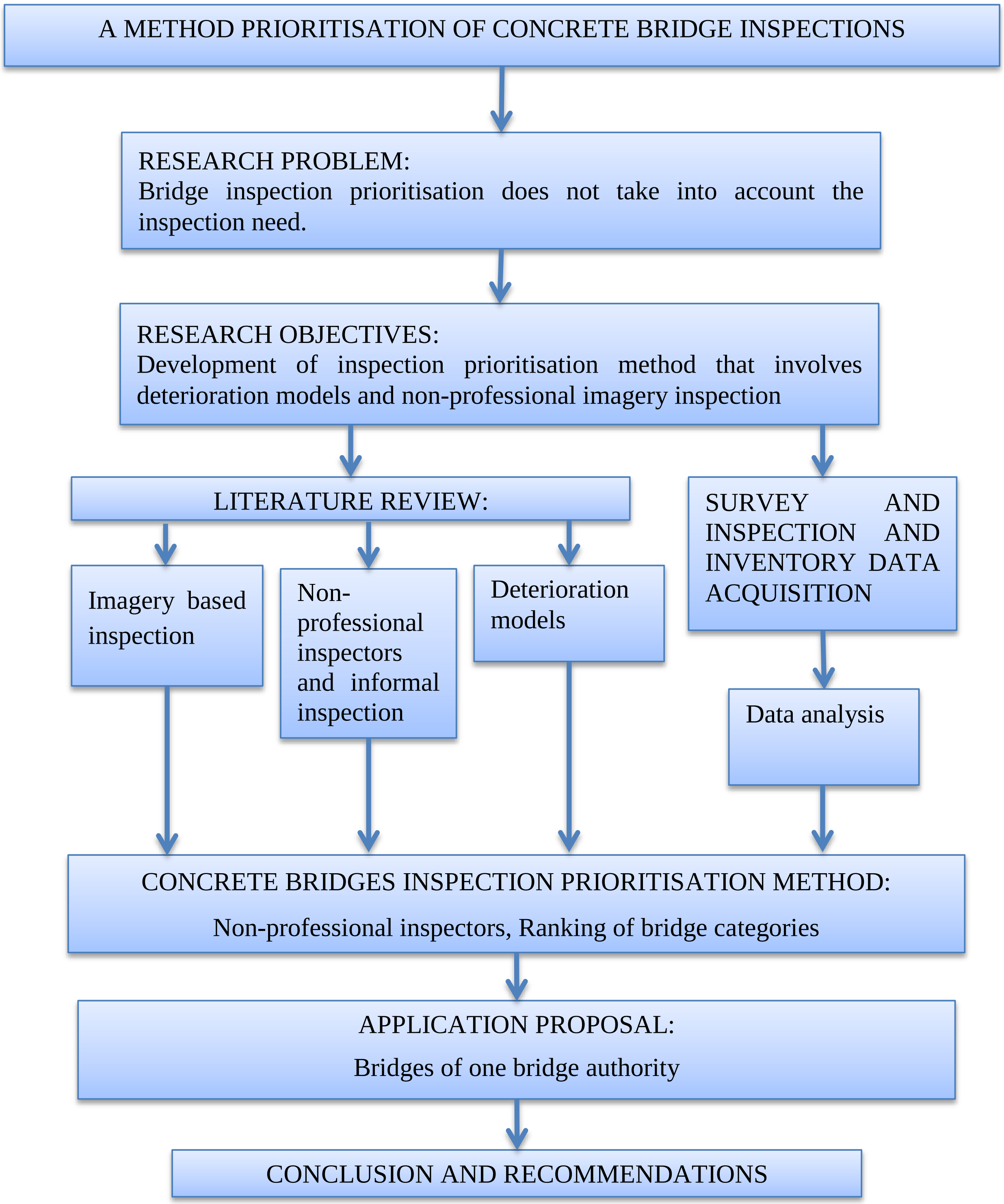


Figure 3-1. Research design

3.2 Literature review

Chapter 2 presented a literature review which provided bridge inspection practices all over the world in general and in South Africa in particular. This literature review has also provided previous research done on bridges inspection and inspection prioritisation. It reviewed the involvement of community members in road maintenance activities and the use of informal sources in bridge inspection. Finally, a review on the use of deterioration models in concrete bridges inspection has been done.

The literature highlights the need of bridge inspection prioritisation that is based on the inspection need of bridges. However, not enough information about informal inspection and inspection prioritisation in South African bridge authorities could be found in the literature. From this emerged the necessity to conduct a survey amongst South African bridge authorities.

3.3 Data acquisition and analysis

The data used in this study has been acquired from the following sources:

- Survey amongst bridge authorities, and
- Inventory and inspection data from the BMS of SANRAL.

3.3.1 Survey

In order to complete the literature gaps about current practices of bridge inspection in South Africa, a survey was conducted amongst South African bridge authorities. The objectives of this survey was to get more information about:

- Bridge inspection practices;
- Bridge inspection prioritisation methods;
- The use of informal source of information on bridge condition and the use of digital image in defects detection;
- The role of routine maintenance teams in bridge inspection.

The results of this survey was used to decide, more effectively, on the need for a prioritisation method for bridge inspection and to which extent this method may be applied in South Africa.

A survey is a method used to collect information about a statistical sample of a population or, rarely, about the full population. Different techniques such as interview and questionnaires may be used to conduct a survey. Interviews allow the interviewer to give to the respondent more explanation for complex questions and clarify the context of the question. On the other hand, this technique involves high travel and/or communication costs, especially when respondents are scattered over a wide geographical area (Jackson, 2009; Phellas, et al., 2011).

The questionnaire technique is not much affected by geographical location of respondents and give more time to respondents to answer the questions. However, this technique presents a low return rate (Jackson, 2009).

For this research, a questionnaire technique was chosen in order to cope with geographical limitations as the respondents for this survey, who are bridge authorities' agents, are geographically scattered across the country. To improve the return rate, respondents were pre-notified about the survey and a follow up was used after the administration of the questionnaire.

The most used BMS in South Africa is STRUMAN developed by CSIR (Ryall, 2009). The statistical population of this survey was the bridge authorities using STRUMAN. Therefore, the appropriate sampling technique is **purposive sampling** as specific bridge authorities that are relevant to this research have been chosen for the survey (Picardi & Masick, 2014). These bridge authorities are:

- **National:** SANRAL;
- **Concessionaires:** N3TC (N3 Toll Concession), Bakwena, TRAC (Trans African Concessions);
- **Provincial:** Western Cape, KwaZulu-Natal, Mpumalanga, Eastern Cape, North West, Northern Cape, Gauteng;
- **Metros:** Johannesburg, Cape Town, Nelson Mandela Bay, Mangaung.

As an email-based questionnaire was used, the emails of the contact person as obtained from the CSIR within the bridge authorities, was used to send a survey link.

3.3.2 Inventory and inspection data provided by SANRAL

Existing data presents some difficulties such as its quality and the difficulty to be transferred from either hardcopy to softcopy format or one type of softcopy to another (Mouton, 2001). However, as explained in *Section 2.6*, the development of deterioration models typically requires a large amount of data extending over a long period of time. For the purpose of this research, inventory and inspection data from a bridge authority was used to develop bridge deterioration model (s). SANRAL has provided inventory and inspection data of bridges under its jurisdiction. This data has been extracted from the BMS and contains the following:

- ***Inventory data***: Bridge ID, construction year, number of spans, bridge description (road under the bridge, rail under the bridge, river under the bridge, etc.), bridge type (continuous, simply supported, etc.), deck type, etc.
- ***Inspection data***: Bridge ID, inspection date, inspection item (bridge component/element), condition rating for element, condition rating for bridge, condition index, etc.

Before data analysis, data filtering and mining was performed as described in *Section 2.6.2.* This consisted of the removal of duplicate records, abnormal changes in condition rating, records affected by rehabilitation actions, etc.

3.3.3 Research instruments

For literature review, books, journal articles, official and research reports and any other useful and relevant conventional and online materials have been used.

The web-based e-survey service of Stellenbosch University (SUrveys) was used to collect survey data. The online questionnaire used in this tool was prepared using the Checkbox® 4.7 software. The majority of questions were 'closed questions' and an option of 'other' answer was offered wherever possible to avoid question rigidity. In order to increase the respondent rate, a pre-notification email had been sent to all respondents two weeks before the questionnaire link was sent.

3.3.4 Data analysis

Survey data was analysed to give an overview of bridges inspection practices in South Africa. The results was presented in form of charts and graphs using Microsoft Excel ®. This analysis was used to decide on the requirements for an involvement of non-professional inspectors in bridge inspection and image processing for defects detection.

Inventory and inspection data of bridges managed by SANRAL was used to evaluate common defects of bridge components. These defects were categorised to know which can be inspected by a non-inspector without involving any risk on bridge's safety.

Using inspection and inventory data provided by SANRAL, suitable deterioration model type (s) was chosen as it has been explained in Section 2.6.2. Deterioration models for the chosen model types were developed by considering the factors influencing concrete bridge deterioration as they were identified in the literature review. These factors include bridge age, traffic loading, climatic effects, bridge type, bridge description and bridge deck construction method. The influence of the factors on bridge deterioration is determined by means of statistical regression.

The Centre for Statistical Consultations of the University of Stellenbosch assisted in statistical analysis of data and interpretation of statistical results. The STATISTICA® (StatSoft, 2013) analysis software was used for these regression analyses.

The deterioration factors that significantly affect the deterioration of concrete bridge was discussed to determine the order of priority of the bridges in terms of need of inspection.

3.4 Concrete bridge inspection prioritisation method

Based on the information gained through the literature review, it was pointed out that more information is needed about inspection practices in terms of respect to inspection guidelines and involvement of third party in South African bridge authorities. This is information obtained through a survey conducted amongst some South African bridge authorities. A method was thus developed for concrete bridge inspection prioritisation following the needs identified from the results of the survey. The proposed method is based on the information on imagery inspection from the literature review, involvement of non-professional inspectors identified through the surveys, and deterioration modelling results from existing inspection data.

Analysis of inspection and inventory data was also carried out to identify bridge defects that may be inspected by means of non-professional based imagery inspection. The identified defects have been based on, to define the characteristics of photographs to be taken, the camera to be used, the bridge items for which photographs will be taken, and the requirements for involvement of non-professional inspectors.

The regression parameters determined by statistical regression as explained in Section 3.3.4 were used to rank bridge categories as a function of need of inspection of bridges.

Finally, regression parameters could be used to determine the cases in which bridge inspection intervals may be reduced or increased. This was done by determining the most likely period of time in which a bridge may remain in the same condition given its characteristics i.e. bridge type, age, traffic, environment, etc.

CHAPTER 4. Survey results

A survey was conducted amongst bridge authorities to investigate bridge inspection practices in South Africa. The survey was done to fill the gap of the literature by gathering more information about Bridge inspection practices, bridge inspection prioritisation methods, the use of informal source of information on bridge condition and the use of digital image in defects detection, and the role of routine maintenance teams in bridge inspection.

This chapter presents the results of the survey.

4.1 Invitation and return rate

The invitation to participate in the survey was sent to 20 CSIR contact persons at 15 bridge authorities as listed in Section 3.3.1.

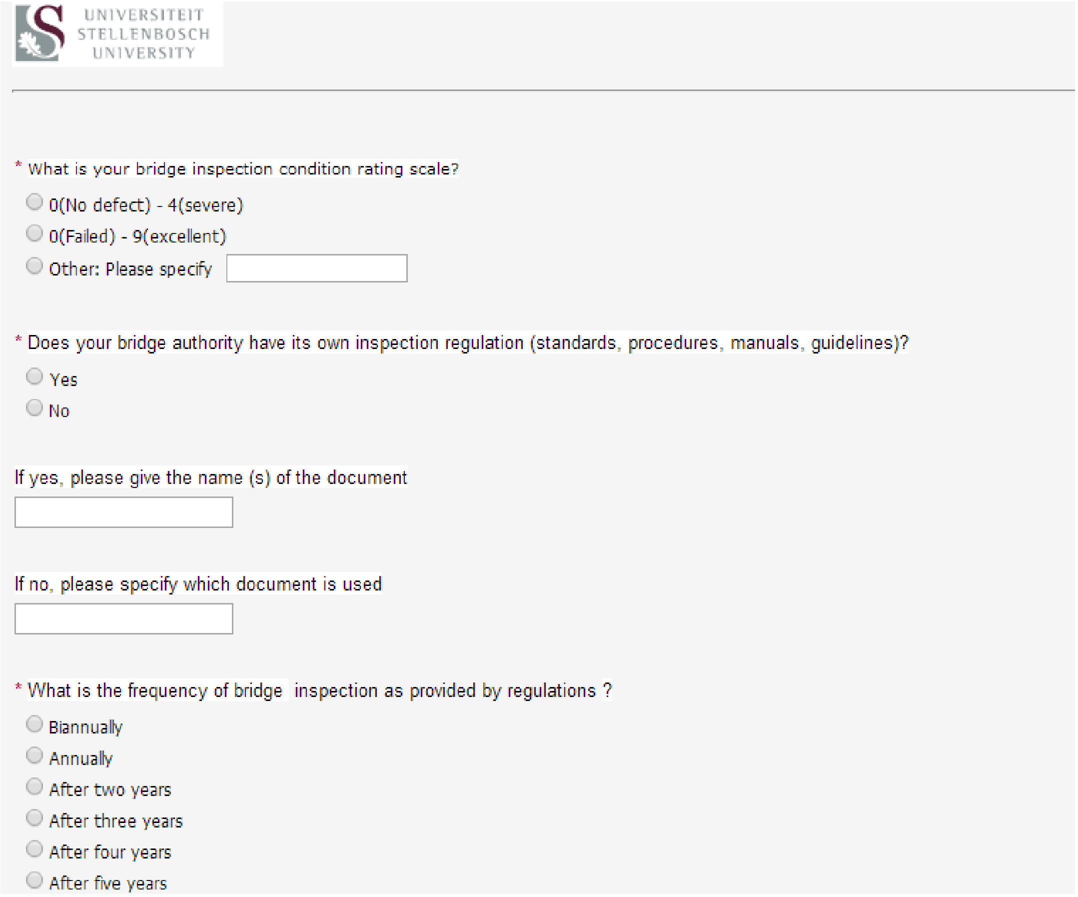
The survey questionnaire comprised 24 questions organised under six sections, namely respondent details, bridge inventory, bridge inspection practice, bridge informal inspection, use of cameras in bridge inspection and routine maintenance program. Figure 4-1 shows an example of the questionnaire web page and the full questionnaire is presented in Appendix 1.

The invitation was sent by email as a web link. The survey web page remained active for one month during which the respondents had access to the survey. 7 recipients responded for 6 bridge authorities. This represents a return rate of 35 % (by contacts) or 40 % (by authorities). Table 4-1 shows respondents rates by authority level.

Table 4-1. Survey response summary

No	Authority	Number of invitees	Responded	Return rate (%)
1	Concessionaire	3	1	33,33
2	Metros	4	2	50,00
3	National	1	1	100,00
4	Provincial	7	2	28,57
Total		**15**	**6**	**40,00**

The difference between the number of respondents and authorities is because, for one of bridge authorities (Mpumalanga Province), two responses have been given: one from BMS consulting company, the other from the bridge authority. The information given by these two respondents is different. The consultant gave a complete and more updated information about the bridges inventory and inspection practice in the bridge authority than the authority's agent. During the analysis of survey data, the information given by the consultant was therefore considered for this authority. However, comments are made on the response of the authority's agent where necessary.



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* What is your bridge inspection condition rating scale?

○ 0(No defect) - 4(severe)
○ 0(Failed) - 9(excellent)
○ Other: Please specify

* Does your bridge authority have its own inspection regulation (standards, procedures, manuals, guidelines)?

○ Yes
○ No

If yes, please give the name (s) of the document

If no, please specify which document is used

* What is the frequency of bridge inspection as provided by regulations ?

○ Biannually
○ Annually
○ After two years
○ After three years
○ After four years
○ After five years

Figure 4-1. An example of questionnaire web page

4.2 Interpretation of results

As explained earlier, this survey had been conducted amongst bridge authorities that use STRUMAN BMS software according to Roux (2014) and the results can therefore not be generalised on the bridge inspection practices in South Africa. The results of survey are presented hereafter. The number of respondents to the survey was small and the data is therefore presented simplistically without basic statistics such as averages and standard deviations in order to avoid a distorted presentation of the actual data.

4.2.1 Inventory

The authority was asked to provide the number of bridges that are managed by the bridge authority, the number of inspected bridges in time intervals of 5 years since 1980 compared to the total number of bridges. The number of bridges per bridge authority in 2014 is shown in Table 4-2. From the responses received the KwaZulu Natal province manage the biggest number of bridges (4345 bridges), followed by SANRAL (3430 bridges) and the smallest number of bridges (136) is managed by N3 Toll Concession (Pty) Ltd.

Table 4-2. Number of bridges by bridge authority

Authority level	Agency Name	Number of bridges
Concessionaire	N3 Toll Concession (Pty) Ltd.	136
Municipal	Johannesburg Roads Agency	1598
Municipal	Transport for Cape Town	601
National	SANRAL	3430
Provincial	KZN Transport	4345
Provincial	Mpumalanga Provincial Government (Consultant)	771

The respondents were then asked to give a description of bridges. This was a categorisation of bridges in five groups: river bridges, road over road, road over rail, rail over road and pedestrian bridges. Three of the six responding authorities gave full information as it is shown in Figure 4-2. In general, river bridges and road bridges crossing roads represent a major part of bridges followed by road bridges crossing railways and the smallest number is rail and pedestrian bridges with a significant proportion of the latter in Cape Town.

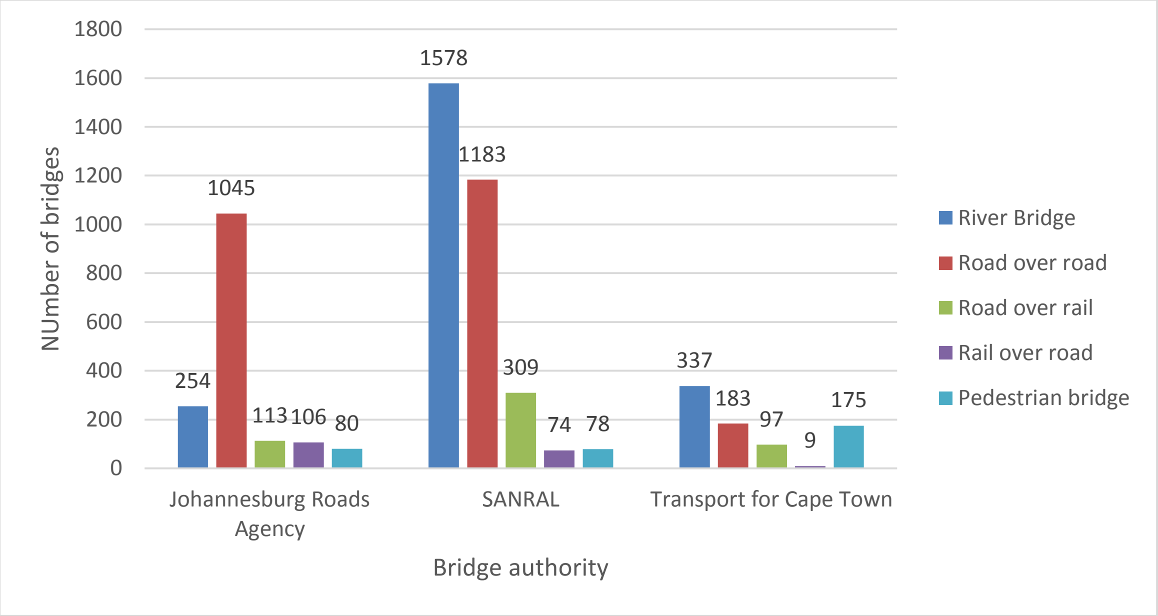


Figure 4-2. Bridge description

4.2.2 Inspection regularity

Respondents were asked to give the inspection frequency and whether it is respected as required in inspection regulations. As shown in Figure 4-3, the inspection interval is 5 years in approximately 83 % of responding bridge authorities and four years in approximately 17 % of responding bridge authorities. In general, the recommended bridge inspection interval of 5 years is used in most bridge authorities.

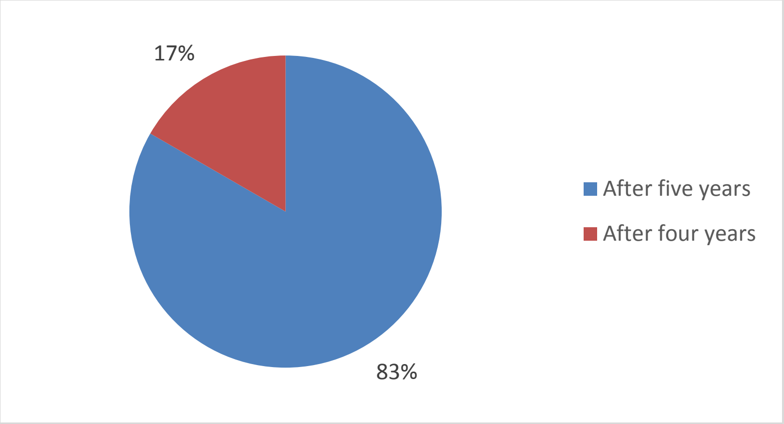


Figure 4-3. Bridge inspection frequency

Figure 4-4 shows that 50 % of the responding authorities respect the inspection frequency as required by TMH19 (2013). The main causes of not respecting inspection frequency is the lack of funds and the lack of personnel as it is shown in Figure 4-5. A lack of experience and non-existence of a responsible section are the other causes of not respecting the inspection frequency.

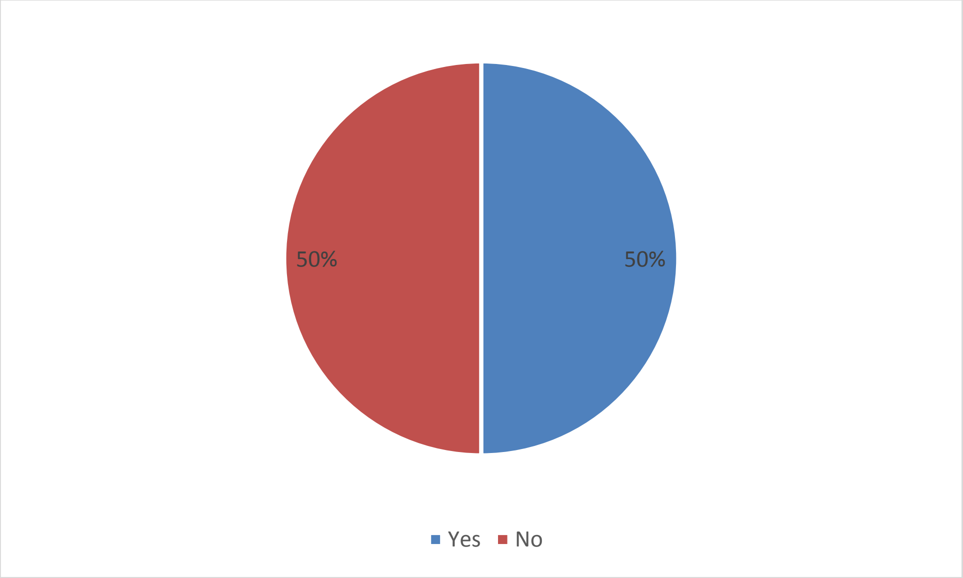


Figure 4-4. Respect of inspection frequency

Figure 4-6 shows the rate between the number of inspected bridges and the total number of bridges over the period between 2005 and 2009. The full complement bridges have been inspected by N3TC and the inspection rate is 50 % in Johannesburg Road Agency. N3TC has respected the inspection frequency since 2000 which might be due to the limited number of bridges managed by this authority.

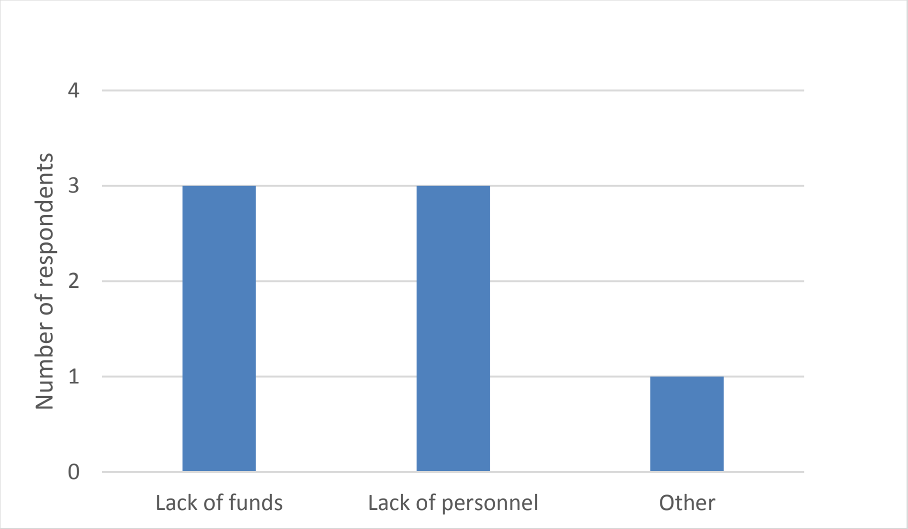


Figure 4-5. Cause of inspection irregularity

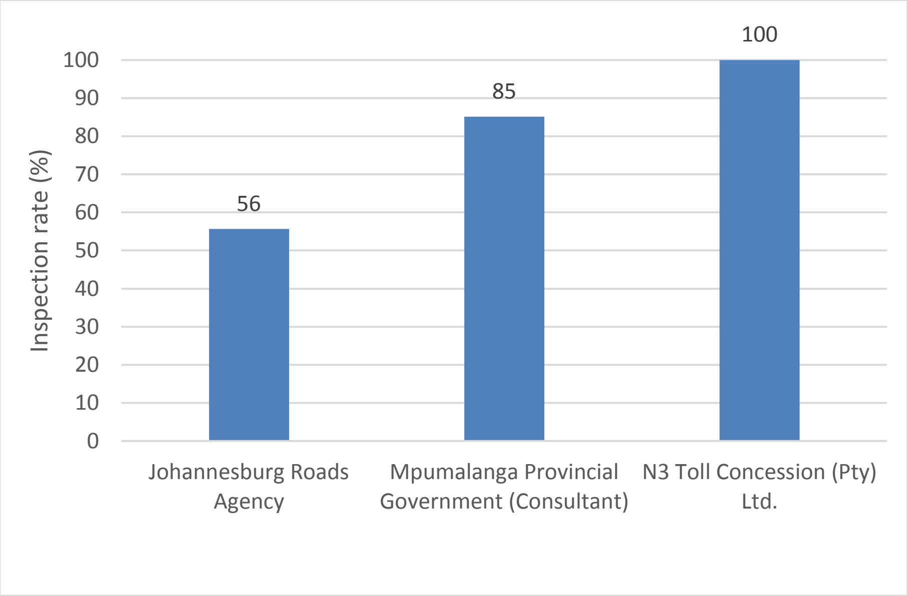


Figure 4-6. Inspection rate 2005-2009

4.2.3 Inspection regulations documents

The bridge authorities were asked if they have their own documents that are used as a guide to bridge inspection. 33 % of bridge authorities answered that they have their own manual as it is shown in Figure 4-7. The documents mentioned by responding bridge authorities are STRUMAN BMS published by CSIR and TMH 22. KwaZulu Natal province uses its own manual “Bridge Management System”.

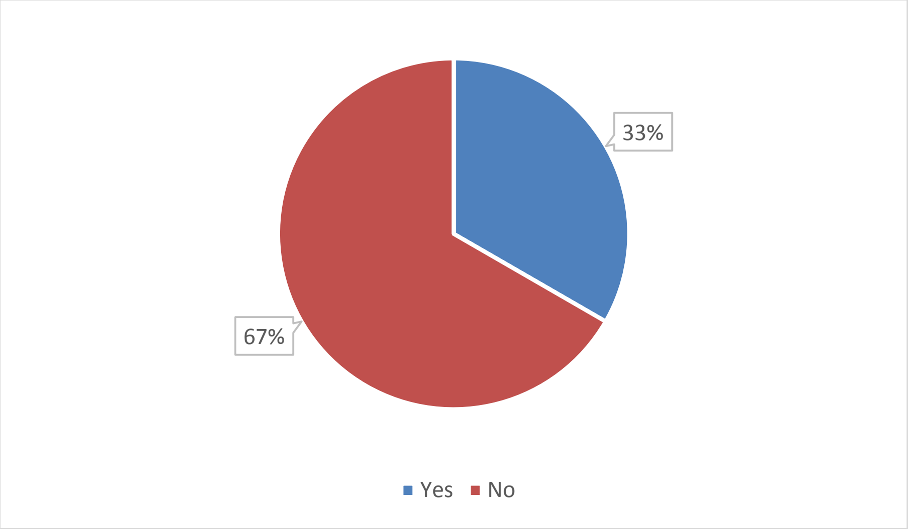


Figure 4-7. Own inspection manuals

4.2.4 Rating system

The bridge authorities were asked to indicate their defect rating system. 83 % i.e. five of the six responding bridge authorities use the DER rating system as shown in Figure 4-8. One bridge authority has its own rating system that measures the bridge condition as a “percentage value”.

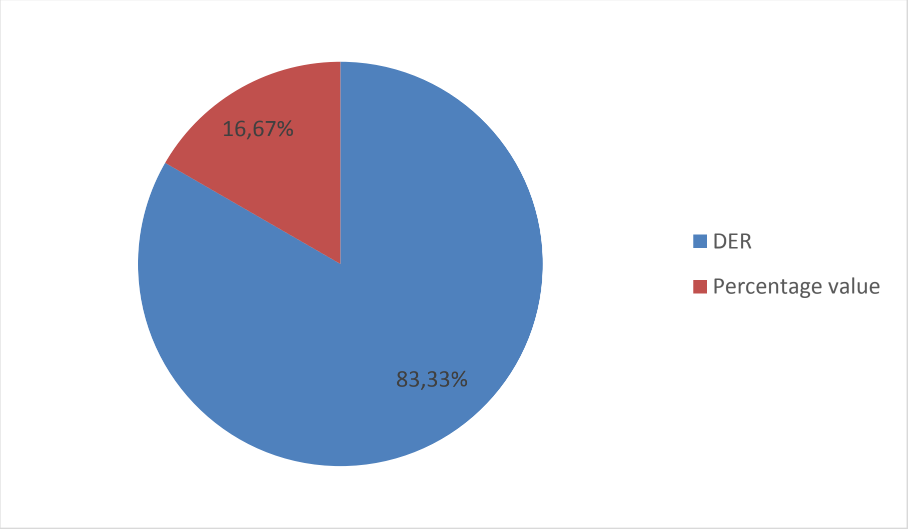


Figure 4-8. Rating system

For this question, different answers were given for Mpumalanga Province. The BMS consultant confirmed the use of DER whereas the provincial agent answered to use a 0 – 9 rating scale. This might be because the provincial agents are still using the old practice that is different from the STRUMAN BMS.

4.2.5 Inspection prioritisation

The respondents were asked if the bridge inspection is prioritised based on defined criteria. The inspection is prioritised in 4 (approximately 67 %) bridge authorities and done systematically in another 2 (approximately 33 %) as shown in Figure 4-9. For N3TC, the limited number of bridges to be inspected (136 bridges), might be the cause for considering a prioritisation method as unimportant as all bridges may be inspected. For Cape Town, the reason given for why there is no prioritisation method is the absence of prior inspections.

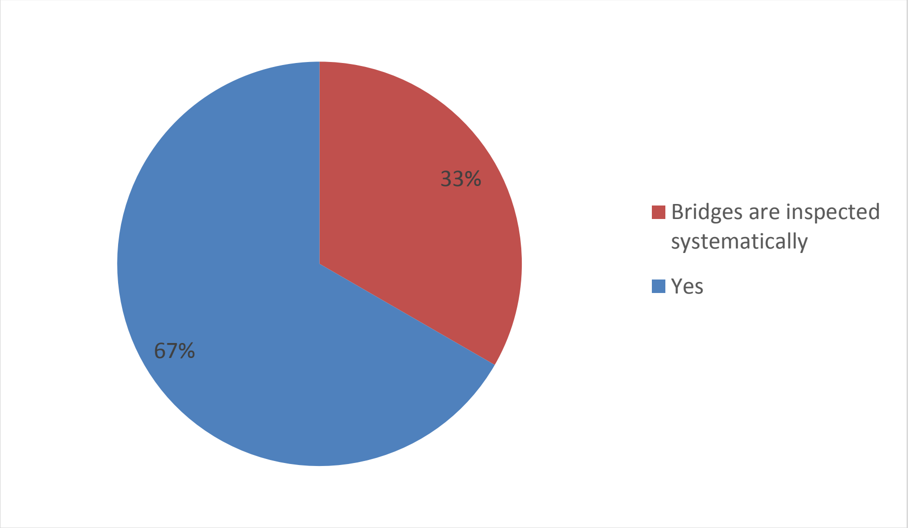


Figure 4-9. Is inspection prioritised?

A risk based approach is the most used in inspection prioritisation except in Mpumalanga where an equitable distribution across all Municipalities is the approach used as shown in Figure 4-10. Note that one respondent didn't give a response to this question.

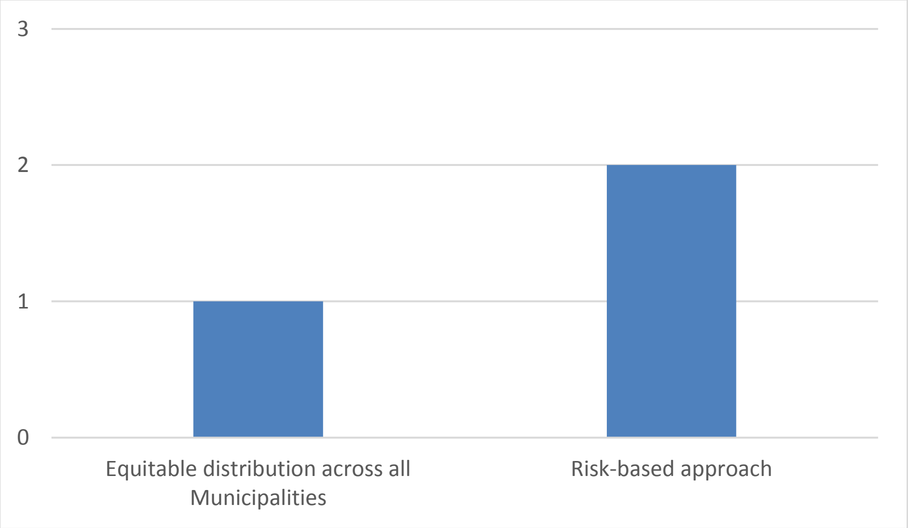


Figure 4-10. Prioritisation tools

“Equitable distribution across all Municipalities” means that according to the available budget for bridge inspections, this is equitably distributed across the Municipalities. This method is not effective as the number and the types of bridges are not the same across the municipalities. In fact, a municipality with a large number of bridges remains with a high percentage of non-inspected bridges which may increase the number of bridges in critical conditions.

With a risk based approach, the bridge with a high risk of failure is inspected first. The risk is defined as the product of the likelihood of failure and the consequence of failure (IIMM, 2011). Engineering judgement may be used to estimate the likelihood and consequence of failure for each type of bridge. The indicators may be age and materials for the likelihood and repair cost and number of users affected for the consequences (IIMM, 2011). The application of a risk based approach in inspection prioritisation thus requires the involvement high skilled and experienced professionals.

4.2.6 Bridge inspectors

The respondents were asked who inspect bridges i.e. private company or authority’s personnel, and the percentage of bridges inspected by each. In 6 responding bridge authorities, bridges are totally inspected by private companies with the exception of KwaZulu Natal and Mpumalanga where authority’s agents inspect respectively 5 % and 1 % of the bridges as shown in Figure 4-11.

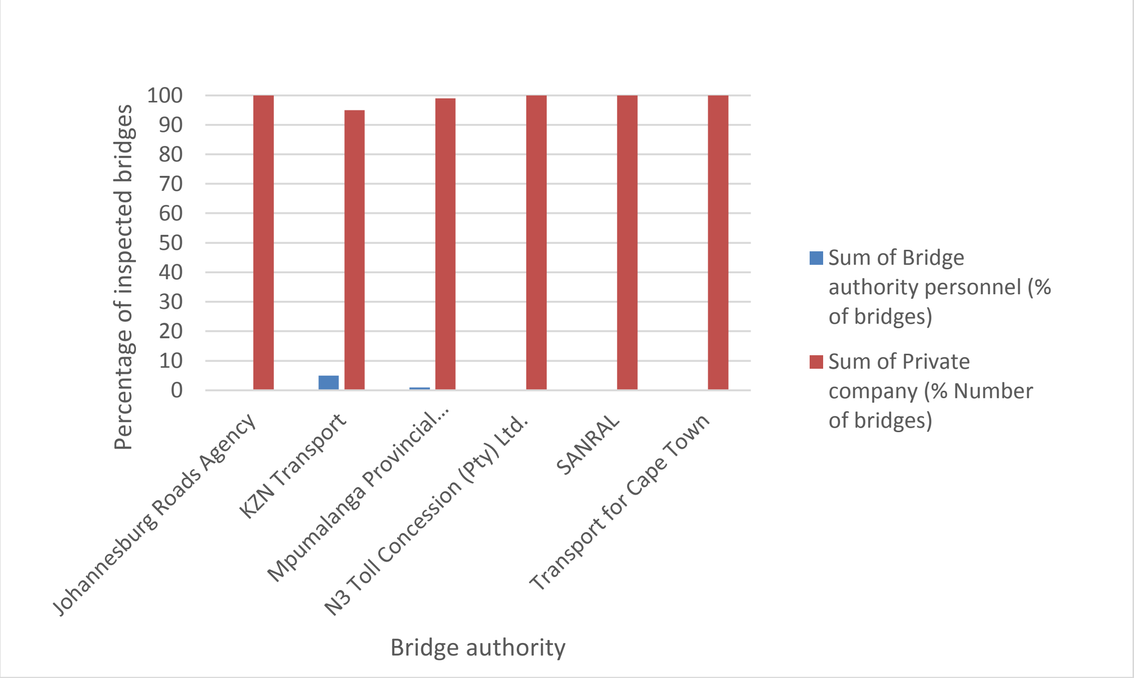


Figure 4-11. Who does inspection?

4.2.7 Imagery inspection

For the question whether digital cameras are used in bridge inspection, all bridge authorities have answered that cameras are used. For all the respondents, the photos are uploaded on the BMS but the

BMS is not able to analyse the photos for defect detection. However, the capacity of BMS software to store photos may be used by storing photos that have been taken for the purpose of further analysis.

4.2.8 Informal Inspections

To a question whether the bridge authority collects information about bridge conditions from third party sources (informal sources), all the respondents answered that they make use of at least one of the indicated sources as shown in Figure 4-12. Routine maintenance crews are the most used informal source with 4 road authorities. Police patrol and anonymous calls are used only in Johannesburg. All the road authorities answered to have other sources of informal information.

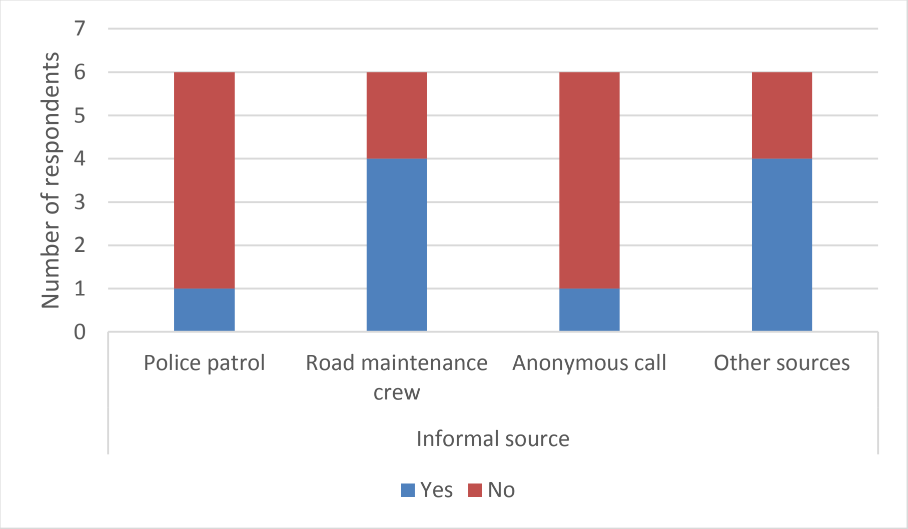


Figure 4-12. Informal sources

The information obtained from informal sources is recorded in the BMS by 2 road authorities and in bridge files by 3 authorities Figure 4-13. All the authorities answered to have another kind of record apart from the BMS.

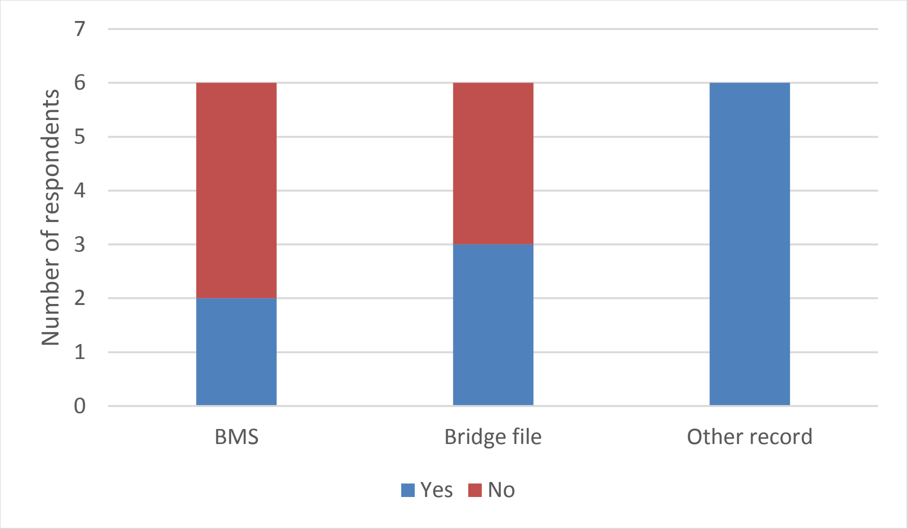


Figure 4-13. Information record

Concerning the use of information, the information from informal sources is used for inspection prioritisation in four responding road authorities and used in bridge maintenance by three authorities as shown in Figure 4-14.

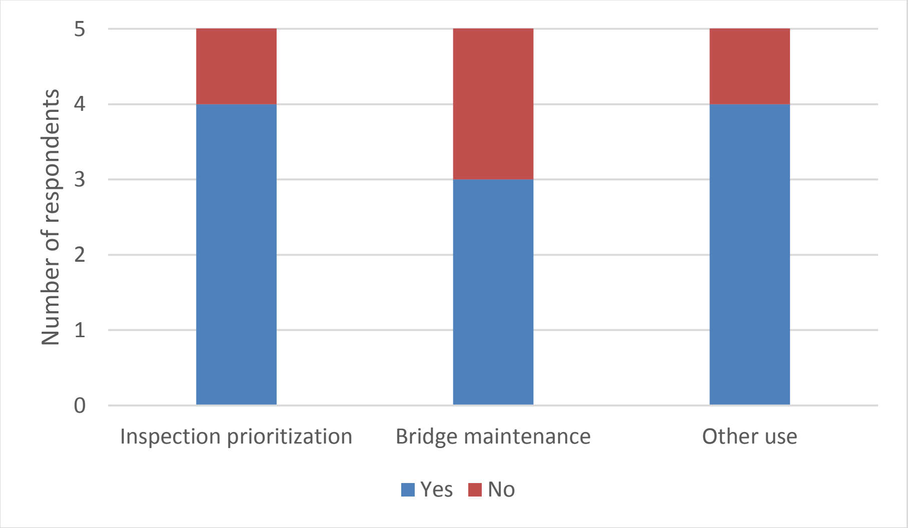


Figure 4-14. Information use

Informal information is collected from different sources and stored by some responding bridge authorities. This information is useful as it can be used in prioritisation of bridge inspection. Routine maintenance crews are among the most used informal sources and may be more involved with small impact on their actual activities.

4.2.9 Routine Maintenance

The respondents were asked if they had routine maintenance programmes. As shown in Figure 4-15, four (approximately 66.7 %) responding bridge authorities answered to have routine maintenance programmes. Cape Town and KwaZulu Natal Province answered not to have such a programme even if the latter confirmed to have some activities in terms of routine maintenance.

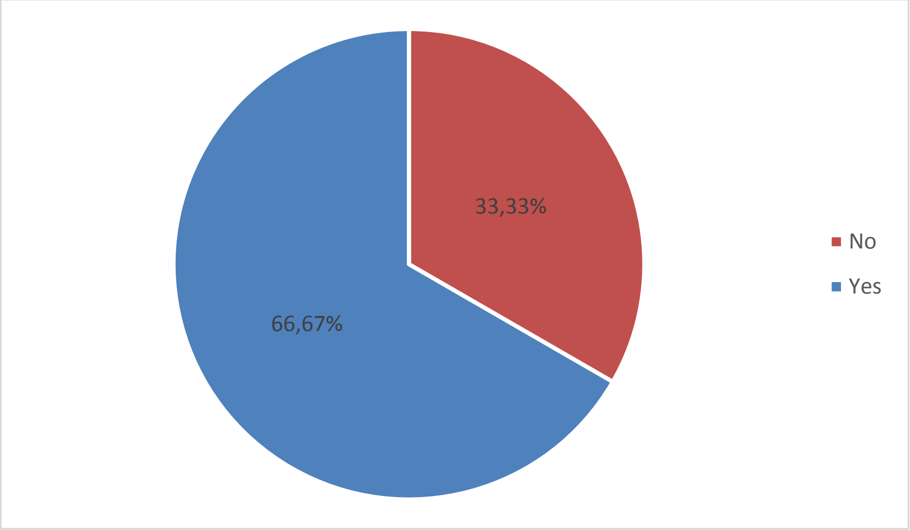


Figure 4-15. Routine maintenance programmes

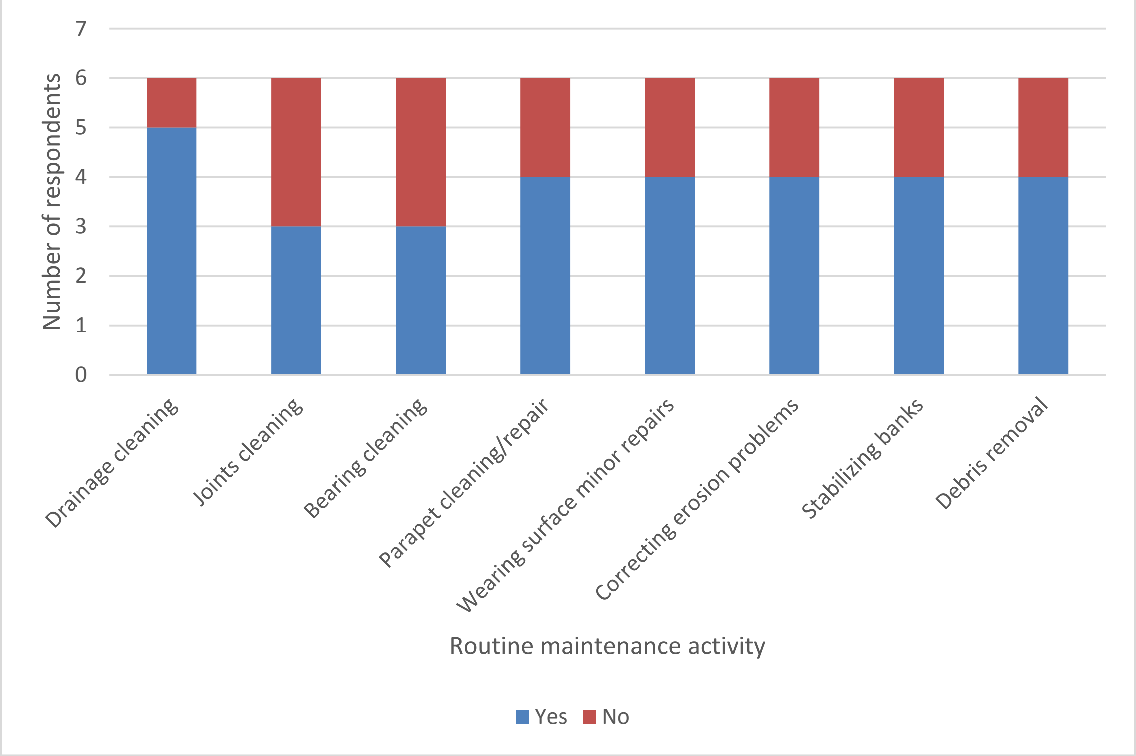


Figure 4-16. Routine maintenance activities

Figure 4-16 shows that drainage cleaning is common routine maintenance activity for all the bridge authorities that have a routine maintenance program. Bearing and joints cleaning are done only by 50 % of the responding bridge authorities.

As shown in Figure 4-17, routine maintenance activities are mostly carried out totally by private companies with the exception of Johannesburg and Mpumalanga where respectively 30 % and 1 % of routine maintenance is done by the bridge authorities. One respondent didn't give an answer to this question.

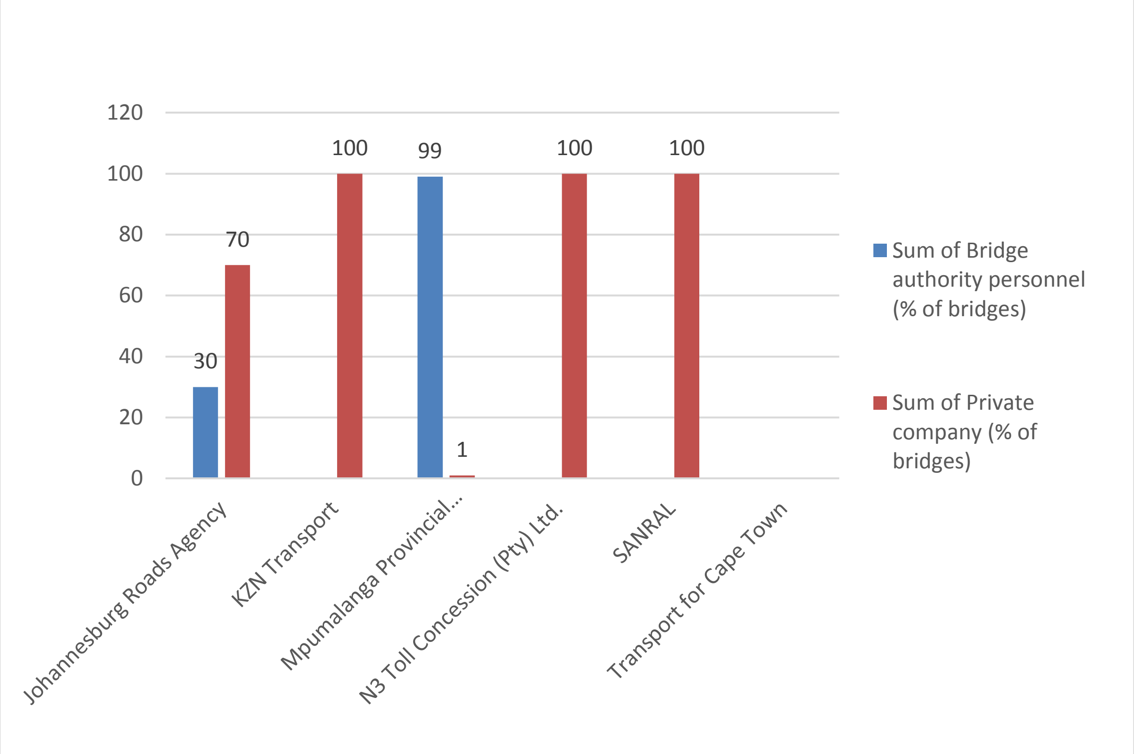


Figure 4-17. Who carries out routine maintenance?

4.3 Findings

Road authorities manage significant number of bridges which mainly consist of road bridges crossing rivers and roads followed by those crossing rails. The bridges are, in general intended to be inspected at a frequency of five years but this is not respected in 50 % of responding bridge authorities. The main cause of not respecting the bridge inspection frequency in South African bridge authorities is a lack of personnel and funds. The lack of experience and a responsible section within the bridge authority has been pointed out as a cause of not respecting the bridge inspection frequency in one bridge authority.

In general, private companies are hired to carry out bridge inspections with a few exceptions where bridge authority's personnel is involved in inspection of a small percentage of bridges.

The preferred defect rating system is DER (Degree, Extent, Relevancy), with a small percentage (17 %) of other rating systems. The use of STRUMAN BMS requires DER as an inspection rating system of defects of bridges' items. Therefore, DER should be the rating system in all bridge authorities in which the survey has been conducted as they have all been indicated by CSIR as

STRUMAN users. On the other hand, a difference between the information given by the BMS consultant and the bridge authority's agent for the same bridge authority has been observed. This might be because the implementation of STRUMAN is still in progress in some bridge authorities.

The prioritisation of bridge inspections is done in 67 % of responding bridge authorities. One cause of non-prioritisation is the small number of bridges where a road authority is able to carry out the inspection of all the bridges in respect of the required inspection frequency. Another cause is the absence of prior inspections which causes the absence of information to rely on when prioritising bridge inspections.

The use of cameras in bridge inspection is still at a traditional level where photos are used only for reporting and archival purposes. The BMS software is not able to process photos for defect detection.

In general, the informal information about bridge condition is gathered form maintenance crews and is used mostly in inspection prioritisation and maintenance. This information is stored in BMS by only 30 % of the bridge authorities.

Routine maintenance is done in 66.7 % of road authorities where the common activity is drainage cleaning and some other activities such as cleaning of bearings and joints are done. In general, routine maintenance is 100% carried out by private companies except in one authority where 30 % of routine maintenance is done by the authority itself.

In conclusion, the results of a survey on inspection practices in South Africa shows that bridge inspection frequency is not respected in many bridge authorities. The lack of funds and personnel is the main cause of this situation given by the responding bridge authorities but this may also be a result of insufficient focus on bridge inspections by BMS managers. On the other hand, the bridge authority where the number of bridges is limited, the inspection is done systematically which may be caused by an availability of funds or a result of concession requirements. A bridge inspection prioritisation method is thus needed to inspect bridges in need of inspection to use the available funds in an optimised manner. This could also save funds in bridge authorities where available funds for bridge inspection are not limited.

Routine maintenance is already involved in the collection of informal information and may therefore be involved in a well-structured collection of data that may be used in bridge inspection prioritisation. This should be more effective if the routine maintenance crews are involved for the bridge components for which they perform maintenance activities such as drainage cleaning, cleaning of bearings and cleaning of joints.

These findings together with a deterioration model developed in the following chapter, are taken into account in the development of an inspection prioritisation method of bridges.

CHAPTER 5. Development of deterioration model

In the literature review, the types of deterioration models were investigated and advantages and disadvantages of each type were given. A deterioration model development procedure has also been given. In this chapter, a deterioration model of bridges managed by SANRAL is developed. The regression parameters were determined and used to explain the bridge condition as a function of age, number of spans, bridge age, bridge description, deck construction method, bearing type, expansion joint type, and bridge region. Section 5.1 gives an overview of inventory and inspection data used in the development of the deterioration model. The data is then prepared by discussing variables and by giving associated frequencies in Section 5.2. Section 5.3 deals with the choice of the model type and the reasons of the choice. Sections 5.4 and 5.5 deal with the development and the evaluation of the model, and the interpretation of regression results. Finally, the conclusion and an example of the use of the regression parameters is given in Section 5.6.

5.1 Data compilation

The South African National Road Agency Limited (SANRAL) is a public institution that has a mandate to finance, improve, manage and maintain the national road network of South Africa. This network comprises approximately 3000 bridges.

The inventory data of bridges that has been provided contains information about the construction year of bridges, number of spans, construction materials and methods, bridge type and bridge description. It also gives the types of bearings and expansion joints for the bridges.

The inspection data provided by SANRAL contains approximately 258 000 records. These are bridge sub-item and item ratings in the DER (Degree Extent Relevancy) system. These ratings have been used to calculate Average Structure Condition Index (ASCI) for every sub-item which in turn served to calculate item and bridge ASCI as it is described in Section 2.4.1.

Figure 5-1 summarises inspection records provided by SANRAL. It shows that more than 70 % of bridges have been inspected only once during the period of 14 years i.e. between 1998 and 2012. Figure 5-2 shows the number of inspections per year during the same period. Two main rounds of inspection were carried out; the first in 2005 and 2006 and the second in 2011 and 2012.

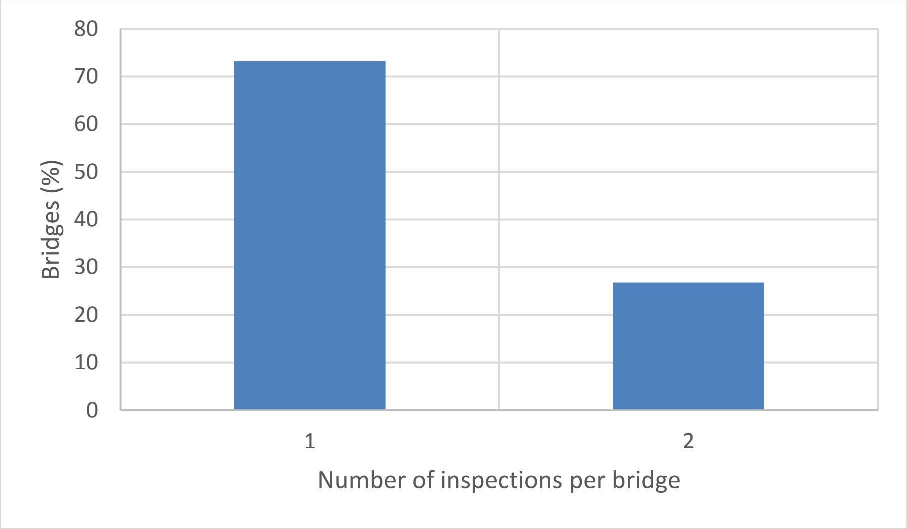


Figure 5-1. Percentage of bridges versus the number of inspections in the period 1998-2012

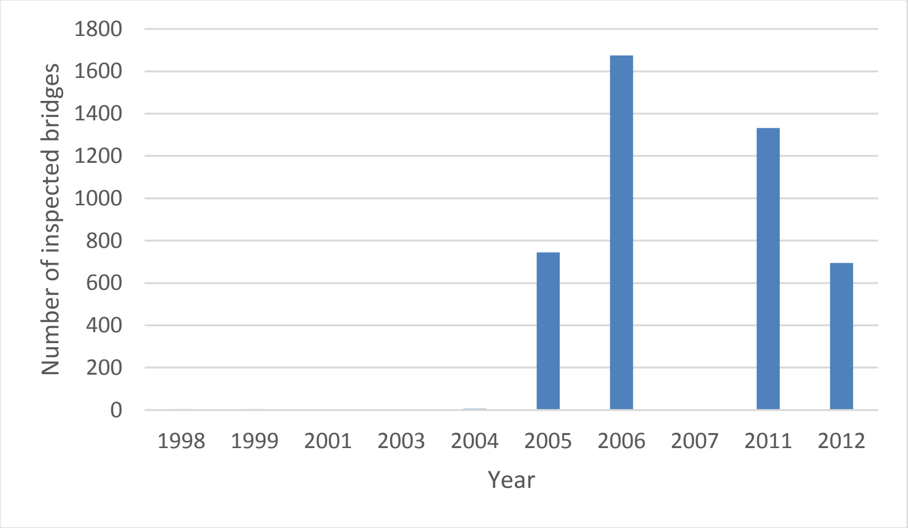


Figure 5-2. Number of inspections per year

Figure 5-3.shows the bridge inspection interval between two consecutive inspections for the bridges that had more than 1 inspection in the period between year 1998 and 2012. A small number of bridges (0.14%) has been inspected after 5 years. A greater percentage has been inspected after 6 years (71.33%) and 7 years (27.84%).

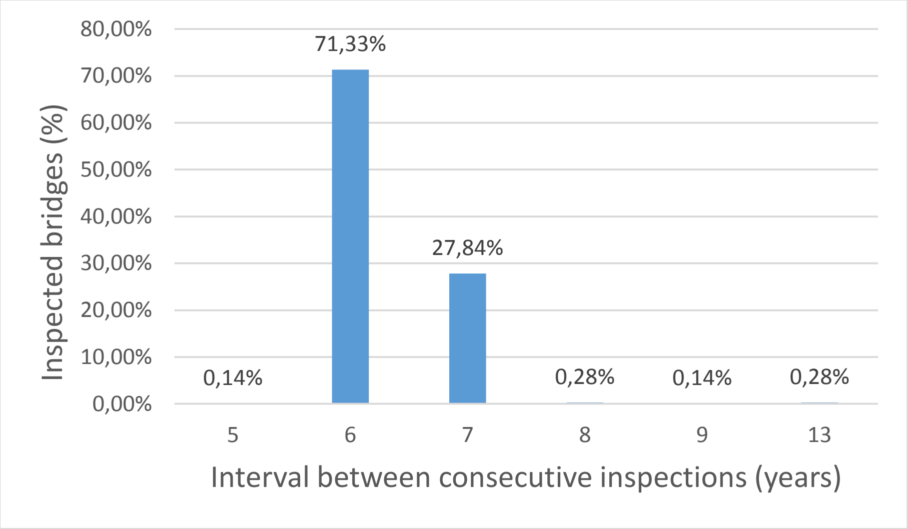


Figure 5-3. Interval between two inspections (SANRAL inspection data)

For the purpose of this study, only bridges with no missing inventory information have been considered. These are approximately 2500 bridges.

Figure 5-4 shows the average of bridge ASCI versus bridge age for all the data provided by SANRAL. It shows that the condition of SANRAL bridges reduces from approximately 95 to approximately 87.5 between 0 and 10 years. The Average Bridge ASCI remains constant (approximately 87.5) till the age of 55 years which should depend on maintenance activities. After 55 years, the Average Bridge ASCI reduces again with age. However, the records about the rehabilitation activities have not been given which means that the real picture of the condition of SANRAL bridges as a function of bridge age may differ from the one given by Figure 5-4.

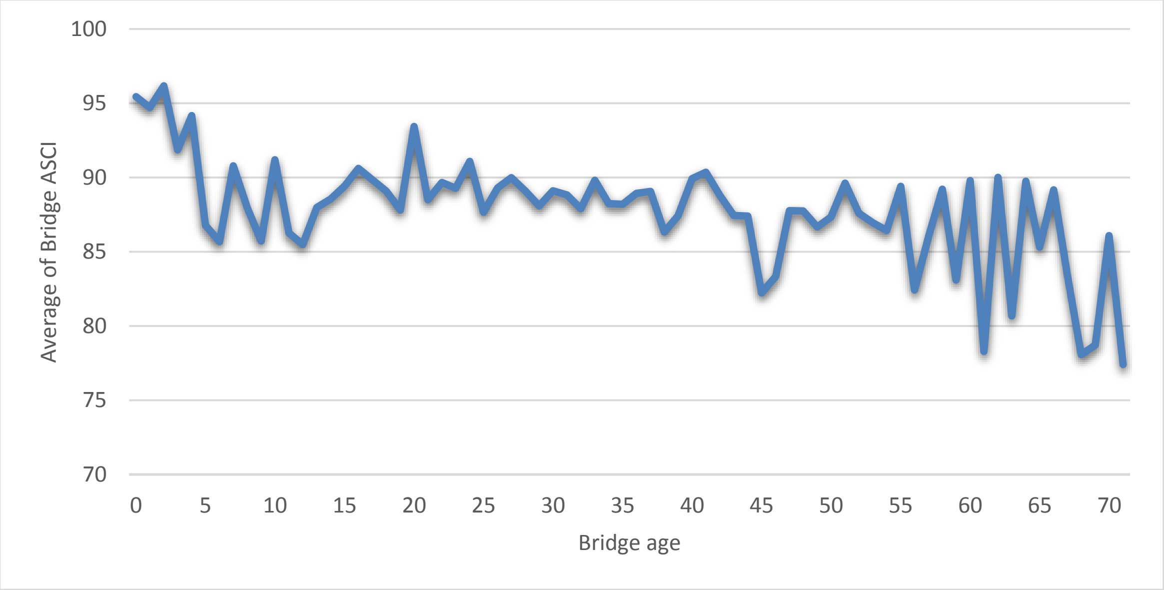


Figure 5-4. Average of ASCI versus Bridge age

5.2 Data mining

This section consist of data filtering which is performed in order to eliminate inspection data affected by rehabilitation, duplicated records, inspector's subjectivity, abnormal sudden drops in ratings, and miscoding of inspection ratings.

In the DER rating system, the condition of bridges are described by the condition indices. The Average Structure Condition Index (ASCI) is one of these indices. ASCI is an indication of the average condition of the structure and can be used to rank structures in terms of condition and to allocate structures to condition categories (TMH19, 2013). For this reason, ASCI is used to describe bridge condition. As it is required in TMH19 (2013), before the inspection data is used to calculate ASCI, the DER ratings had been adjusted as follows.

- The records with Degree rating = -2 (Unable to inspect) are adjusted as it is explained in Section 2.4.1 and the item inspection records with a Degree rating = -1 (Not Applicable) were removed.
- According to TMH19 (2013) the Degree rating will always be greater than or equal to the R-rating. Conversely**,** the R-rating can never be greater than the D-rating. For the cases where R-ratings are greater than the D-ratings, the records were considered as rating errors and removed.

After calculation of the ASCI at bridge level, duplicate records were removed. These are records with the same Structure ID (Structure Identification number), inspection year and ASCI value. As the method developed in this study is for concrete bridges, the records corresponding to other bridges than concrete were removed.

Finally the records for which all the inventory characteristics for bridges were not available were also removed.

The final dataset that was used to develop the deterioration model contains approximately 4900 records.

The data does not contain rehabilitation records which are believed to have been conducted on some of bridges as there are old bridges with a relatively high ASCI as shown in Figure 5-5. To reduce the influence of rehabilitation some limits have been imposed to old bridges by the researcher. As it is shown in Figure 5-5 and Figure 5-6 few inspection points of bridges older than 55 years have a condition index value of more than 90 %. This is the same for bridges older than 60 years with condition indices greater than 80 %. To partially address the issue of missing rehabilitation records, the records that correspond to the following intervals have been removed:

- The data points with age greater than 55 years and ASCI greater than 95 %
- The data points with age greater than 57,5 years and ASCI greater than 90 %
- The data points with age greater than 60 years and ASCI greater than 85 %

For further improvement of data by reducing rehabilitation impact, the bridges for which ASCI is greater for an inspection than the previous inspection have been identified and the increase in ASCI was calculated. However, there might be other causes of increase of ASCI than bridge rehabilitation. These causes may be the inspector's subjectivity, error of rating of the previous inspection, etc. (Phares, et al., 2004) found a significant variability in the assignment of condition ratings and other forms of inspection documentation in USA bridge inspection that lead to incorrect condition ratings. Therefore, the records corresponding to an increase of ASCI by more than 10 have been removed from the dataset.

Note that this action cannot completely fix the rehabilitation influence on the data but only to reduce it as there may still be repaired bridges among those with one inspection record.

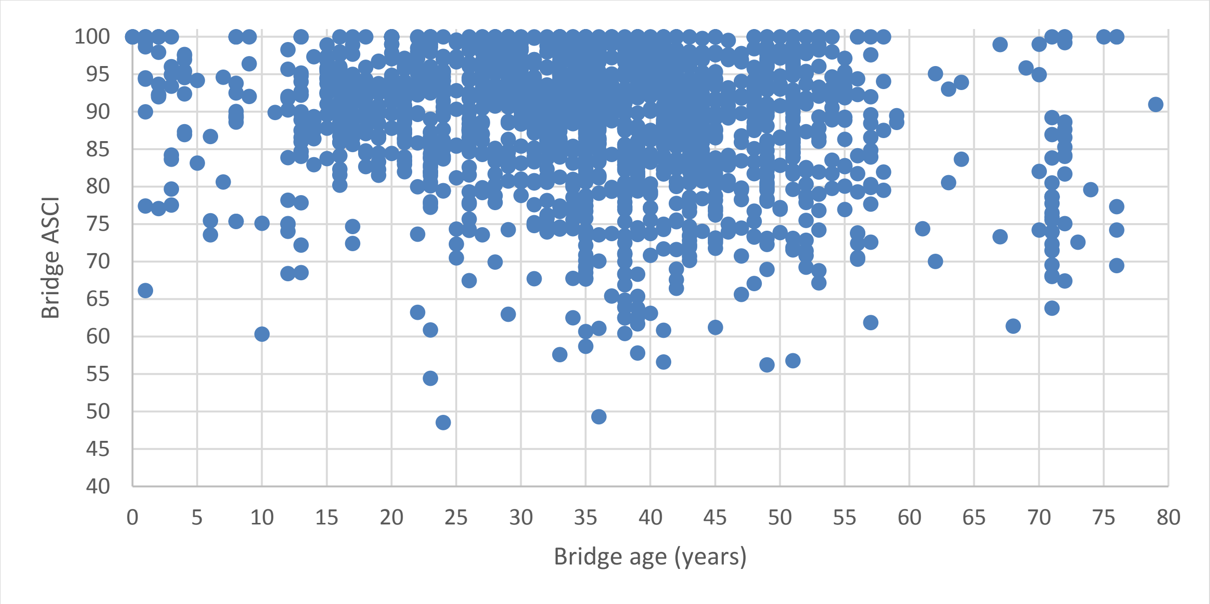


Figure 5-5. Age versus ASCI for 2011 inspection

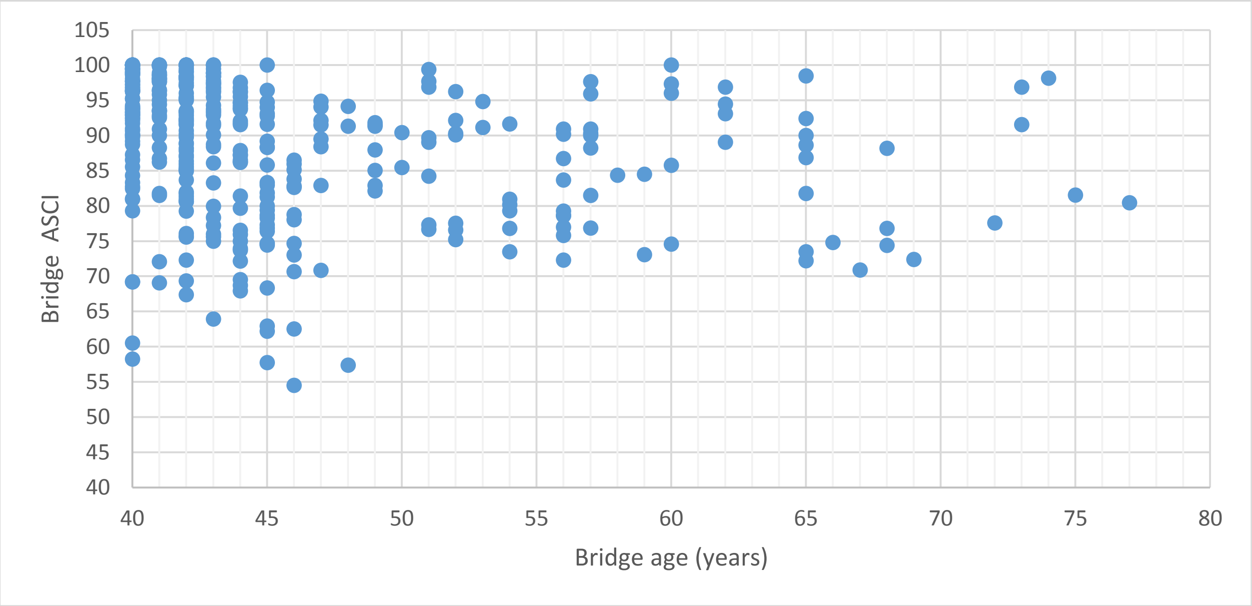


Figure 5-6. Age versus Bridge ASCI for 2012 inspection

5.2.1 Dependent variable.

The objective of the development of the deterioration model is to describe the condition of bridges as a function of their characteristics. TMH22 (2013) categorises the condition of highway structures, bridges included, as a function of their condition index as it is shown in Table 2-9. For this reason, the dependent variable is ASCI for the deterioration model to be developed. For the purpose of this work, a multiple regression model and a binary logistic regression model have been chosen as it is explained in Section 6.5.

For the multiple linear regression model, the scale of the dependent variable (ASCI) varies from 0 (bridge in critical condition) to 100 (bridge in excellent condition). For ASCI below 70 i.e. warning level, a bridge has some components subject to evident deterioration that need to be subjected to preventive maintenance or some isolated items need to be renewed (TMH22, 2013). 70 is therefore considered as the trigger of inspection need.

For the binary logistic regression model, the deficiency level is fixed at 70 i.e. a bridge or item with an ASCI less than 70 will be considered as deficient and thus in need of inspection, and a bridge with an ASCI greater than 70 will be considered as non-deficient.

5.2.2 Independent variables

The deterioration model is intended to predict the ASCI of bridges as a function of influencing factors. According to the data provided, the considered factors are construction year of bridges, number of spans, bridge description, deck construction methods, bridge type, bearing types and expansion joint types. In order to reduce the number of variables similar bridge characteristics have been grouped together by the researcher as shown in Table 5-1, Table 5-2, Table 5-3, Table 5-4, and Table 5-5. Some of the characteristics have been removed as they are not relevant to this research or they are infrequent so that their impact on the ASCI is low.

The data used does not contain information about bridge aspects such as road class, traffic volume, environment, etc. Recall that these aspects were identified in literature as factors that influence the deterioration of bridges. However, the deterioration model will be developed using the available data to demonstrate the approach and the results will be interpreted accordingly.

Table 5-1. Bridge description grouping

BRIDGE DESCRIPTION	
Type	**Group**
Agricultural underpass	Agricultural underpass
Canal bridge (under road)	Canal bridge (under road)
Pedestrian bridge	Pedestrian bridge
Rail over road	Rail bridge
Rail over Road & Rail	
Pedestrian underpass	Road bridge
Road bridge	
Road bridge - N Route over	
Road over Rail	
Road over Road	
Road over Road & Rail	
Utility bridge	Utility bridge
Viaduct (valley bridge)	Viaduct (valley bridge)

Table 5-2. Deck construction grouping

DECK CONSTRUCTION METHOD	
Type	**Group**
Cast insitu on stationary falsework & rotated into position	Cast insitu
Cast insitu segmental	
Cast insitu on stationary falsework	
Combination cast in-situ with steel girders	Steel girder
Connecting of structural steel elements	
Steel girders with launched concrete slab	
Erection by crane	Precast
Precast beam and insitu slab	
Precast Reinforced Concrete beams and in-situ deck slab	
Precast segmental	

Table 5-3. Bridge type grouping

BRIDGE TYPE	
TYPE	**Group**
Arch filled	Arch
Funicular	
Open spandrel	
Solid spandrel	
Open ribbed spandrel arch	
Articulated structure	Articulated structure
Balanced cantilever continuous	Cantilever
Balanced cantilever with drop in spans	
Single & double cantilever with drop in spans	
Single cantilever with drop in spans	
Box culvert	Culvert_Cellular
Box or cellular culvert	
Multiple box with drop-in spans	
Cable stayed	Cable stayed
Continuous main spans and simply supported end span	Continuous
Continuous	
Continuous with drop in spans	
Simply supported and continuous	
Multi-continuous	
Lattice truss girders	Lattice truss girders
Simply supported	Simply supported
Frame (incl multiple frames Trestle)	Frame
Strutted frame	
Trestle frame	

Table 5-4. Bridge type grouping

BEARING TYPE	
TYPE	**GROUP**
Concrete hinge bottom of pier	concrete
Concrete hinge top	
Concrete hinge top & bottom	
Concrete Pads	
Rocker concrete	
Elastomeric , tetflon and stainless steel plate	Elastomeric (neoprene)
Elastomeric neoprene	
Laminated elastomeric pad & spherical bearing	
Neoprene pads	
Monolithic	Monolithic
Malthoid (slip membrane)	
Rubber pad	Rubber
Rubber pads between steel plates	
Spherical bearing with adapter plates	Pot or spherical
Spherical bearing without adapter plates	
Pot bearing without adapter plates	
Pot or Spherical	
Rocker	Other
Rocker Steel	
Roller	
Steel plates	
Lead or steel sheeting	
Lead sheeting	
Pin	
Uplift bearings	
Glacier	
Guide	
Impregnated board	
Other	
None	None

Table 5-5. Expansion joints grouping

EXPANSION JOINT TYPE	
TYPE	**GROUP**
Asphaltic plug	Asphaltic plug
Thorma Joint	Thorma Joint
Buried under surfacing	Buried under surfacing
Elastomeric concrete nosing with compression seal	Elastomeric
Elastomeric concrete nosing with elastomer	
Elastomeric concrete with steel edge and sealant	
Bolted down elastomeric	
Elastomeric concrete with joint filler	
Elastomeric concrete nosing with elastomer element in metal runner	
Conc nosing with elastomer element in metal runner	
Sliding steel plates	Sliding steel plates
Concrete nosing with compression seal	Other
Joint sealant	
Concrete nosing with steel edge & compression seal	
Concrete nosing with silicone sealant	
Maurer	
Modular	
Open joint (concrete nosing & metal runner)	
Epoxy nosing with steel edge and compression seal	
Open joint (concrete nosing only)	
Epoxy nosing with compression seal	
Sealant and waterstop	
Metal finger joint	
Concrete nosing with joint filler	
Steel cover plate	
Custom built	
Steel plate buried under surfacing	
Glacier "s" joint	
Concrete nosing with steel edge and sealant	
Joint sealant with cover plate	
Fibre board	
Flexcell	
Glacier Robek - bolt down joint	
Epoxy nosing with compression seal and waterstop	
None	None

Each effect (variable) and effect level (variable value) in the development of the model is discussed hereafter.

5.2.2.1 Bridge region

The bridges managed by SANRAL are divided into 4 regions that correspond to SANRAL's administrative regions. These regions are Western, Northern, Eastern and Southern regions as shown in Figure 5-7.

Figure 5-7. SANRAL's regions (SANRAL, n.d.)

Figure 5-8 shows the macro climatic regions of Southern Africa used in design of flexible pavements for interurban and rural roads (TRH4, 1996). Compared to SANRAL regions, the main part of Northern and Eastern Regions are located in wet and moderate regions and Western Region is generally located in dry climatic region by exception of its southern part that includes Cape Town.

Therefore, SANRAL regions cover different climatic regions and this parameter is included in the model to evaluate the influence of climate on the deterioration of bridges. The number of bridges per region is shown in Figure 5-9.

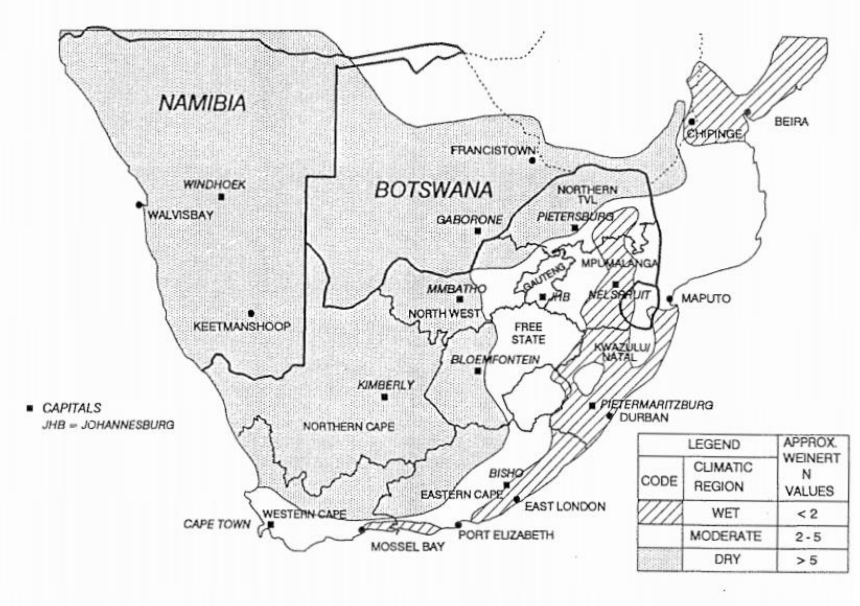


Figure 5-8. Macro climatic regions of Southern Africa (TRH4, 1996)

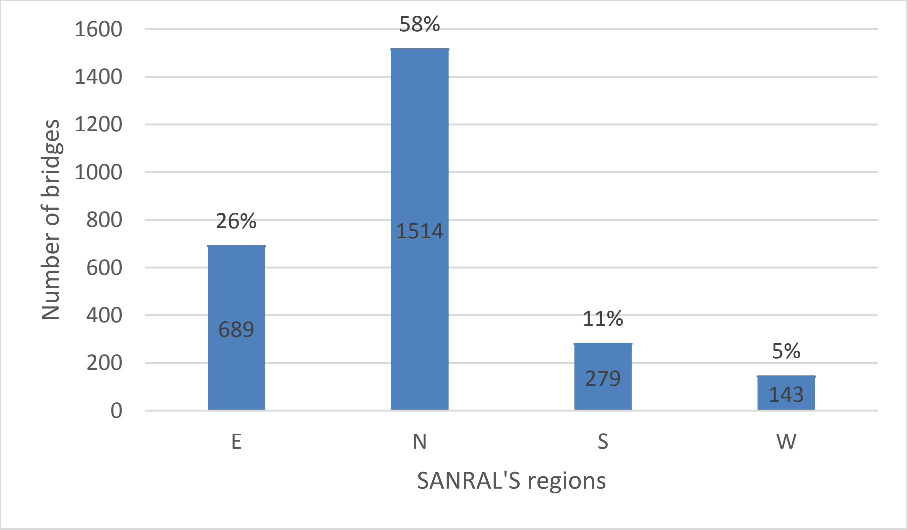


Figure 5-9. Number of bridges per region

5.2.2.2 Age of bridge

The age of bridges in the dataset used to develop the deterioration model varies from 0 to 77. Figure 5-10 shows the frequencies. The majority of bridges has an age between 20 years and 55 years which are therefore bridges built during the period between 1967 and 1985. This means that, in general, bridges are of a medium age.

The age that is used in the analyses corresponds to the date of inspection and is calculated as the difference between the year of construction and the year of inspection.

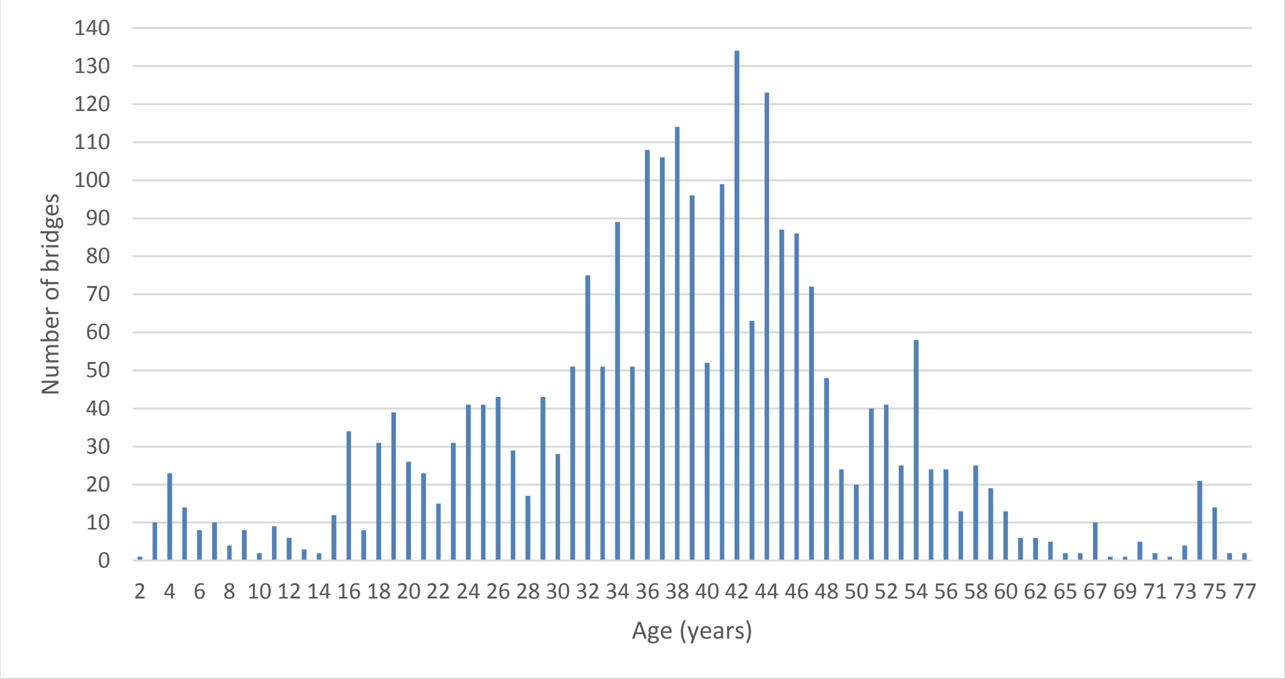


Figure 5-10. The age of bridges in 2014

Bridge ASCI versus construction year of the bridge is shown in Figure 5-11. It is observed that ASCI is generally lower for bridges built before 1955 but are still above 70 i.e. they are, in general, in good condition. Bridges built after 1984 are, in general, in good condition with higher ASCI.

ASCI of bridges seems to be very good even for old bridges. This might be due to rehabilitation or reconstruction activities that may have taken place. The ultimate availability of rehabilitation records would allow to adjust the age of bridges by calculating it as a difference between reconstruction or rehabilitation date and the inspection date.

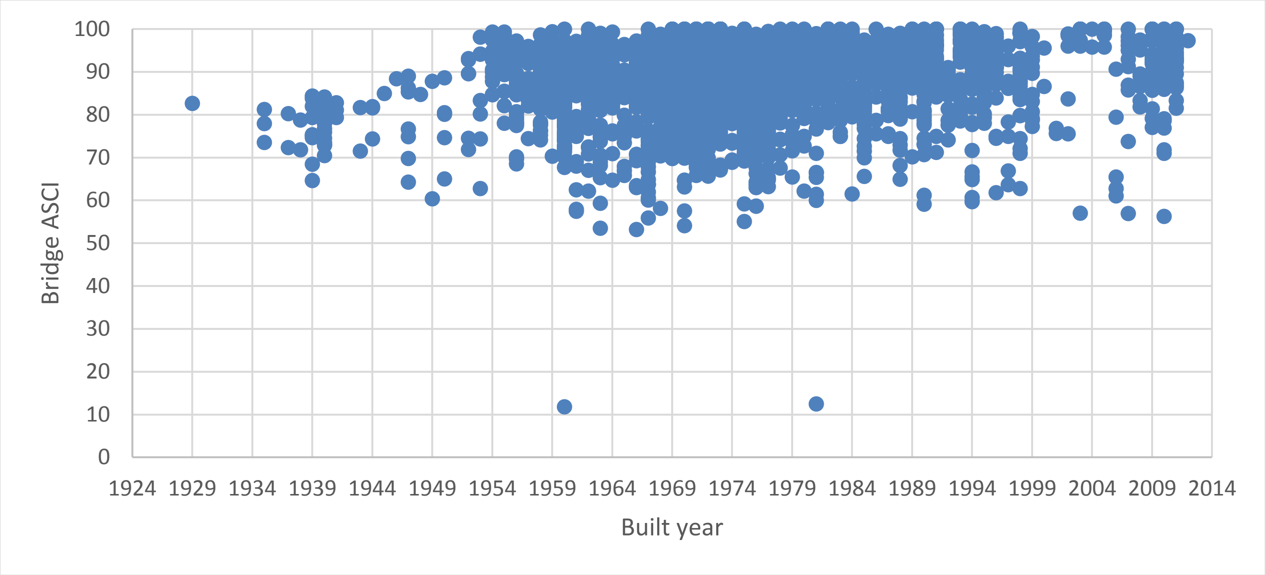


Figure 5-11. Bridge ASCI versus Year Built

5.2.2.3 Number of spans

The number of records by number of spans of bridges are shown in Figure 5-12. The majority of bridges are short, with the number of spans less than 10.

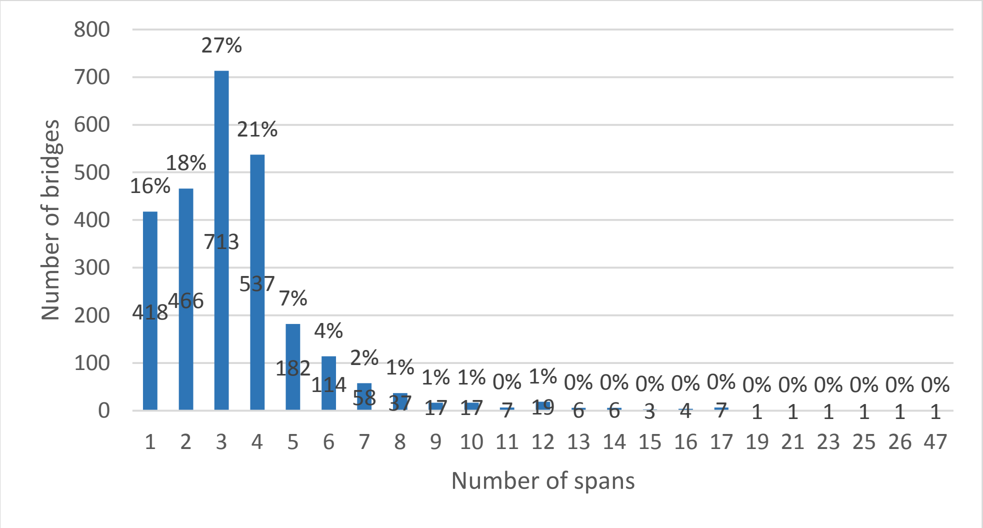


Figure 5-12. Number of spans

5.2.2.4 Bridge description

Bridge description refers to the function of the bridge. It depends on the obstacle crossed by the bridge (road or river) and the use of the bridge (road, rail, pedestrian). As shown by in Figure 5-13, a large number of bridges cross roads or rivers. Pedestrian bridges and rail bridges are also observed.

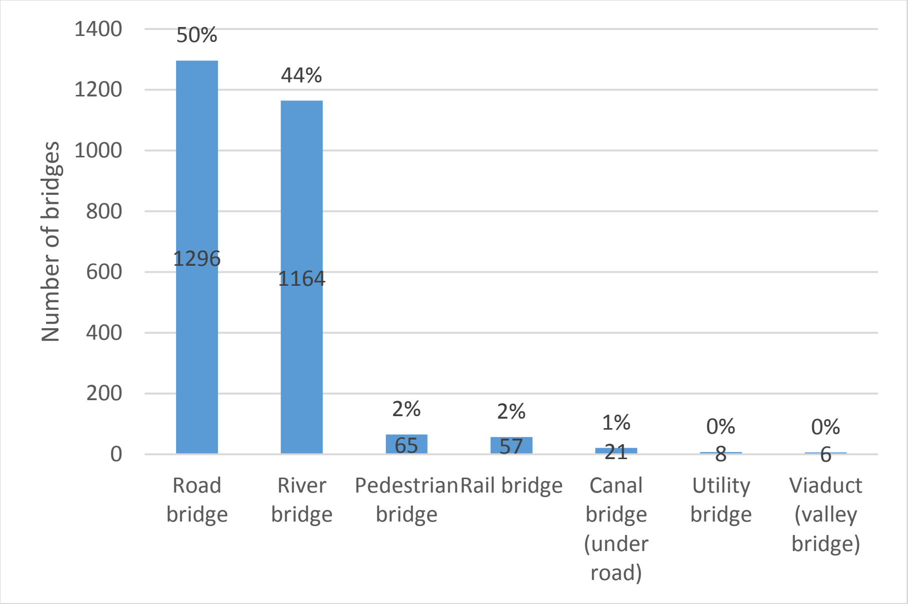


Figure 5-13. Bridge description

5.2.2.5 Bridge type

Bridge type refers to the structural system of the bridge. The bridges are mainly simply supported and continuous beam type bridges as shown in Figure 5-14. Frame, cellular and arch are other types but limited in number.

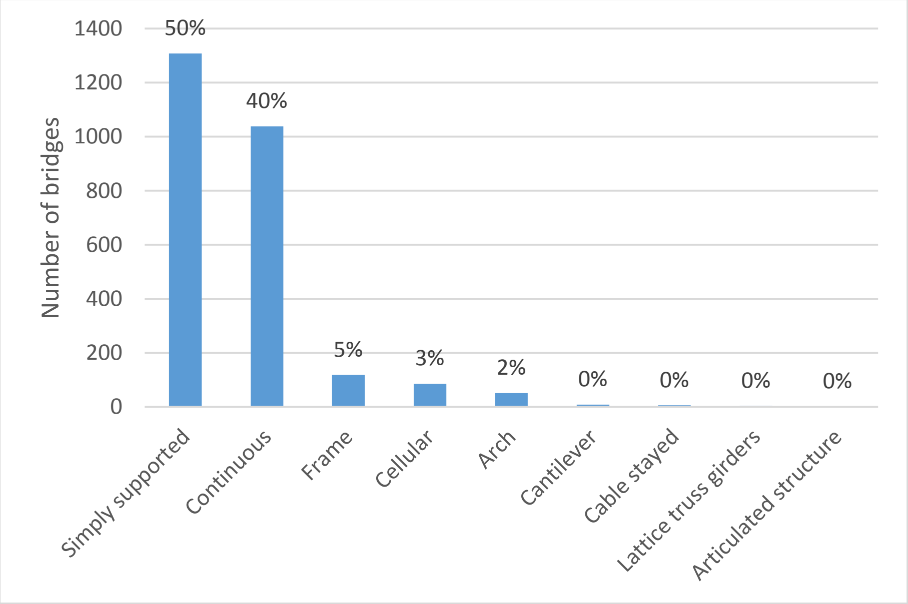


Figure 5-14. Bridge type

5.2.2.6 Deck construction method

The deck construction method refers to the method of construction of the bridge deck. The bridges with steel girders have been grouped together because their deterioration mechanisms differ from other types of bridges. The bridge decks are, in general cast in situ with a low percentage of precast bridges as shown in Figure 5-15. There is a low number of bridges with steel girders and even less built with the balanced cantilever method.

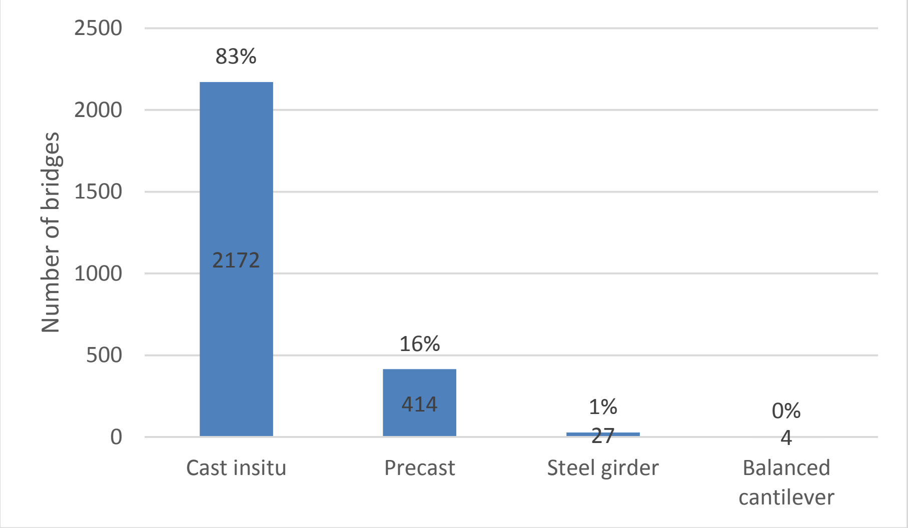


Figure 5-15. Deck construction method

5.2.2.7 Bearing type

Bearing type refers to the type of bearing that transfer the bearing reactions from the superstructure to the substructure of the bridge. The presence of bearings is considered regardless of the position and number of bearings (on some or all piers/abutments). Bearing fixity is also ignored. Where a bridge has more than one type of bearing, the bearing type that is large in number is chosen. The bearings are in general malthoid, elastomeric and pot or spherical as shown in Figure 5-16.

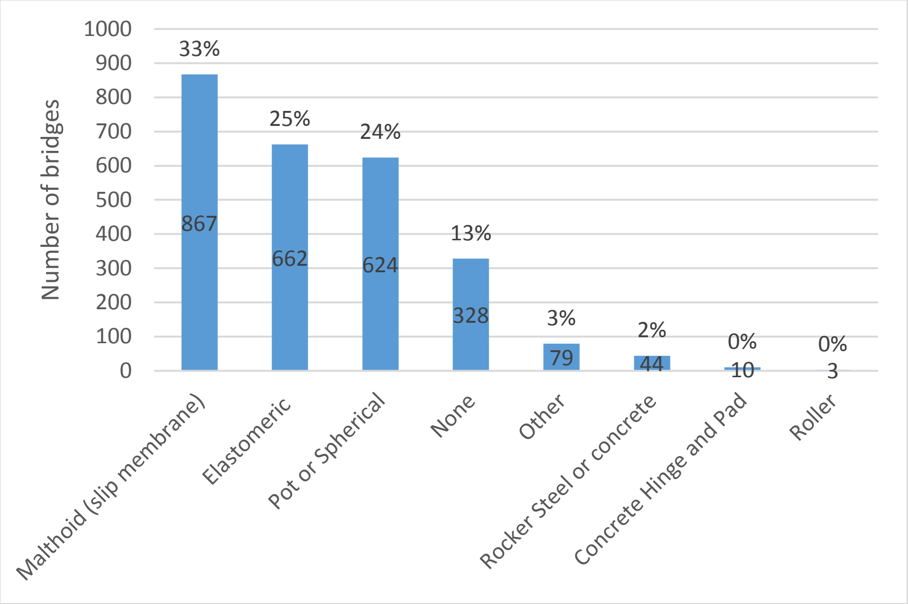


Figure 5-16. Bearing type

5.2.2.8 Expansion joint types

Expansion joint type refers to bridge components that carry load and provide continuity over the gaps between bridge and abutments or two spans of a bridge. The most common expansion joint type is "buried under surfacing" and the other frequent types are asphaltic plugs, elastomeric and thorma joints as shown in Figure 5-17.

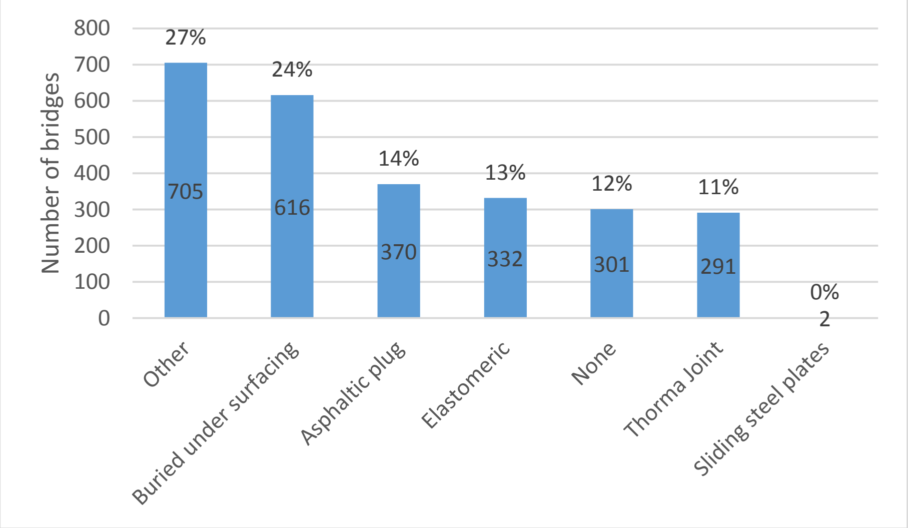


Figure 5-17. Expansion joint types

5.3 Choice of model type

The choice of model type for the analyses is based on the advantages and disadvantages of each type and their facility for implementation. Based on this, the model types that have been chosen for the bridge inspection prioritisation method are the multiple linear regression model and the binary logistic regression model as explained later in Section 6.5.

For this research, the dependent variable is bridge ASCI which is a continuous variable. Furthermore, the deterioration model that is developed is intended to be used in a bridge inspection prioritisation method and it would be therefore an advantage that the model is easily understood and used by bridge engineers and managers. For the above reasons, a multiple linear regression is chosen to develop this model.

Logistic models may be used to develop a model from this dataset after transformation of the dependent variable in a binary response as explained the Section 6.2. However, a logistic model is not developed in this research.

5.4 Development and evaluation of the model

Before performing the regression on the variables defined in Section 5.2, an evaluation of correlation between the variables has been carried out as explained in Section 2.6.2. Table 5-6 shows the Variance Inflation Factors (VIF) for each level of effect (variable value) calculated using STATISTICA®. The reference levels of effect are excluded from analysis, and therefore do not appear in any results including collineality analysis. As explained in Section 2.6.1, a VIF larger than 10 is an indication of serious multicollineality problems. As it is shown in Table 5-6, all the VIF are less than 10. There is no serious problems of collineality that may influence the regression and all the variables are therefore included in the regression models. Note that some dummy variables for which observations occur infrequently has been removed from the analysis.

Based on the available dataset of SANRAL bridges, 7 independent variables have to be included in the development of the deterioration model. 5 of the independent variables are qualitative and have a certain number of categories. These categories correspond to the characteristic groupings presented in Section 5.6.2. This large number of variables requires an advanced statistical analysis software for the estimate of the regression parameters and STATISTICA® has been chosen to develop the deterioration model.

A test of significance of the independent variables in the model has been done for the dependent variable, Bridge ASCI. Table 5-7 shows the p-values of all variables (the level of variables taken as reference are not included). All the p-values are less than 0.05 except the variable “number of spans”. This means that these independent variables have significant effects on “Bridge ASCI” with a confidence interval of 95 %.

Table 5-6. Results for multicollinearity test between variables

Effect	Level of Effect*	Variance Inflation factor
Bridge Description	Road bridge	2.43
Bridge Description	Rail bridge	1.26
Bridge Description	River bridge	2.46
Bridge Type	Continuous	2.79
Bridge Type	Simply supported	3.22
Bridge Type	Cellular	1.33
Bridge Type	Frame	1.24
Deck Construction Method	Precast	1.19
Bearing Type	Elastomeric	1.53
Bearing Type	None	2.00
Bearing Type	Malthoid (slip membrane)	1.98
Bearing Type	Rocker Steel or concrete	1.99
Bearing Type	Pot or Spherical	1.92
Expansion Joint	Other	2.24
Expansion Joint	None	3.42
Expansion Joint	Thorma Joint	2.57
Expansion Joint	Asphaltic plug	2.28
Expansion Joint	Elastomeric	2.77
Region	N	1.09
Region	E	1.17
Region	S	1.14
Age		1.19
Number of spans		1.15

* The levels of effect taken as reference are not listed.

Table 5-7. Univariate Tests of Significance for Bridge ASCI

Effect	**Degrees of Freedom**	**p**
Intercept	1	0,000000
Bridge Description	3	0,000000
Bridge Type	4	0,000000
Deck Construction Method	1	0,001106
Bearing Type	5	0,000000
Expansion Joint	5	0,000032
Region	3	0,000031
Age	1	0,000000
Number of spans	1	0,636337

As explained in Section 2.6.2, the removal of non-significant variables may not be beneficial as it may lead to the loss of valuable information contained in deleted variables. This is why all the variables are maintained in the regression analysis. The results of multiple linear regression are shown in Table 5-8 and Table 5-9. The regression parameters corresponding to each variable are given in column “Bridge ASCI Parameters” of Table 5-8 and are discussed in Section 5.5. The column “Bridge ASCI p” of Table 5-8 gives the p-value of variables which is used to evaluate the significance of the regression parameters. The estimated regression parameters are significant with a confidence level of 95 % for p-values less than 0.05.

The coefficient of correlation R^2 is 0,131644 i.e. 13.2 % as shown in Table 5-9. This value means that, with confidence level 95 % (p-value <0.05), the model can explain only 13.2 % of the variations in the bridge condition index (Bridge ASCI). The remaining part of variations may be explained by other factors that have not been included in the model because of the missing of data. These may include the traffic volume, climatic and environment, rehabilitations and repairs, etc. Once this information has been sourced in a follow up study, the coefficient of correlation needs to be calculated.

Tolliver and Lu (2001) developed a multiple regression model for bridges of the Northern Plains Region (USA) that could explain approximately 56 % of the variations by including bridge type, bridge design, bridge operating rating, average daily traffic, and the state in which the bridge is located.

Veshosky, Beidleman, Buetow, and Demir (1994) developed deterioration models including only bridge age and the average daily traffic (ADT) to compare steel and prestressed concrete where the coefficients of determination (R^2) is about 13%. The authors argued that the omitted and missing independent variables such as design, construction, maintenance and environment limited the expectation of high values of determination coefficients.

The two examples given above show that the coefficient of determination estimated for this model could be expected to be as low as it is determined because a significant number of variables have not been included in the model.

According to the explanations given above, this model is therefore used only to demonstrate the use of the bridge inspection prioritisation method developed in this research.

Table 5-8. Estimate of regression parameters

Effect	**Level of Effect**	**Bridge ASCI Parameters**	**Bridge ASCI p**
Intercept		92.92827	0
Number of spans		-0.02484	0.636337
Age		-0.09576	0
Bearing Type	Elastomeric	1.47139	0.000007
Bearing Type	Malthoid (slip membrane)	-0.62115	0.069981
Bearing Type	None	0.1442	0.762497
Bearing Type	Other	0*	*
Bearing Type	Pot or Spherical	1.38974	0.000168
Bearing Type	Rocker Steel or concrete	0.35357	0.680747
Bridge Description	Pedestrian bridge	0*	*
Bridge Description	Rail bridge	-1.85802	0.009873
Bridge Description	River bridge	-1.85062	0.000001
Bridge Description	Road bridge	0.30792	0.400092
Bridge Type	Arch	0*	*
Bridge Type	Cellular	1.83366	0.00703
Bridge Type	Continuous	0.40024	0.322686
Bridge Type	Frame	-1.96241	0.000622
Bridge Type	Simply supported	-1.06838	0.012072
Deck Construction Method	Cast insitu	0*	*
Deck Construction Method	Precast	0.62269	0.001106
Expansion Joint	Asphaltic plug	-0.74757	0.016367
Expansion Joint	Buried under surfacing	0*	*
Expansion Joint	Elastomeric	0.35312	0.316122
Expansion Joint	None	0.98646	0.015093
Expansion Joint	Other	-0.45761	0.083476
Expansion Joint	Thorma Joint	0.8165	0.018957
Region	E	-0.84661	0.000888
Region	N	-0.62844	0.003894
Region	S	1.27133	0.000153
Region	W	0*	*

* The corresponding level of effect is taken as reference.

Table 5-9. Regression summary for the whole dataset

Dependent Variable	Multiple R	Multiple R^2	Adjusted R^2	Degreed of freedom of the Model	p-value
Bridge ASCI	0,362828	0,131644	0,126969	23	0,00

5.5 Test of the model and interpretation of regression parameters

The regression of Bridge ASCI on independent variables gives the best results when all the variables are included despite the low correlation coefficient. Because of a low correlation, regression parameters explains a small part (13 %) of the variations in bridge ASCI. However, the significance of the variables shows that independent variables have significant effects on the bridge ASCI. Therefore, the regression parameters are used in this prioritisation method for descriptive purposes. This is done by evaluating the effect of dummy variables on bridge ASCI relatively to one dummy variable taken as a reference. The estimates of the regression coefficients, as given in Table 5-8 are interpreted hereafter. The effect of dummy variables for which regression parameters are not significant is not significantly different form that of the dummy variable taken as reference. These are therefore interpreted as reference dummy variable.

5.5.1 Regression intercept

The intercept of the regression is 92.92827. This means that, when other characteristics of the bridge are “fixed”, the average ASCI is 92.92827 for a new bridge (0 year age). When other characteristics of the bridge are considered, the specific intercept varies as explained later on in Section 5.6.

5.5.2 Effect of age on bridge deterioration

The coefficient of the variable “age” is -0.09576 as shown Table 5-8. The negative sign means that the age has a reducing effect on bridge ASCI. Therefore, bridge ASCI reduces when a bridge is aging. This is explained by the fact that a bridge in use is exposed to deteriorating factors such as environment actions, and traffic.

As characteristics of a specific bridge do not change, this parameter is determinant for bridge ASCI. For example, for a bridge used for 10 years, the bridge ASCI will reduce by 0.09576 x 10 = 0.96. This is a low deterioration rate when compared to other studies such as Tolliver and Lu (2001) where a bridge substructure is estimated to lose 0.5 of its rating points in 13 years. The rating scale being from 9 (excellent bridge) to 0 (failed bridge), 0.5 points represent approximately 5.5 % of the initial condition. This may be caused by the fact that the bridges are located in more aggressive environmental conditions than South African bridges.

5.5.3 Effect of number of spans on bridge deterioration

The coefficient of the variable “number of spans” is -0.02484. This variable is not significant and its regression parameter is also not significant (p = 0.636337 >> 0.05) and it is not included in the application of this model.

5.5.4 Effect of bridge description on bridge deterioration

The coefficients of levels of effect of bridge description are interpreted relative to pedestrian bridges. The coefficient of rail bridges (-1.85802) and river bridges (-1.85062) are negative. The negative sign means that bridge ASCI would be lower over time for these types of bridge than for pedestrian bridges. The coefficient of road bridge (0.30792) is positive but is not significant i.e. its effect on Bridge ASCI is not different from pedestrian bridges.

With other characteristics of a bridge being equal, a rail bridge would be in a poorer condition than a river bridge, which itself would be in poorer condition than pedestrian bridge. A road bridge would be in a similar condition as a pedestrian bridge.

5.5.5 Effect of bridge type on bridge deterioration

The coefficients of levels of effect of bridge description are interpreted relative to arch bridges. The coefficient of frame bridge (-1.96241) and simply supported bridge (-1.06838) are negative which means that bridge ASCI should be lower over time for these types of bridge than for arch bridges. The coefficient of cellular bridges (1.83366) is positive which indicates that bridge ASCI should be higher over time for this type of bridge than for arch bridges. The coefficient of continuous bridges (0.40024) is not significant i.e. its effect on bridge ASCI is not different from arch bridges.

With other characteristics of a bridge being equal, a frame bridge would be in a poorer condition than a simply supported bridge, which itself would be in poorer condition than an arch bridge. A Cellular bridge would be in a better condition than an arch bridge. A continuous bridge would be in a similar condition as an arch bridge.

This is in compatible with what has been established by Freyermuth, Klieger, Stark, and Wenke (1970) cited in Madanat, Mishalani, and Ibrahim (1995) that the type of bridge affects the rate of deterioration. The authors argued that high flexibility in the deck of simple-spans bridge gives them high deterioration rates when compared to the continuous concrete structures and prestressed decks.

5.5.6 Effect of deck construction method on bridge deterioration

The coefficients of levels of effect of deck construction method are interpreted relative to cast insitu bridges. The coefficient of precast-deck bridges (0.62269) is positive which indicate that bridge ASCI should be higher over time for this type of bridge than for cast insitu-deck bridges.

With other characteristics of a bridge being equal, a bridge with a precast deck would be in a better condition than the bridges with “cast in situ” deck. This may reflect the better quality of construction of precast elements than in-situ concrete.

5.5.7 Effect of bearing type on bridge deterioration

The coefficients of levels of effect of bearing type values are interpreted relative to bridges with “other” bearing types. The coefficient of bridges with malthoid (slip membrane) (-0.62115), rocker steel or concrete (0.35357), and none (0.1442) are not significant i.e. bridge ASCI should be similar over time for these types of bridge as for bridges with “other” bearing types. The coefficients of elastomeric (1.47139), pot or spherical (1.38974) are positive which indicate that bridge ASCI should be higher over time for these types of bridge than for bridges with “other” bearing types.

With other characteristics of a bridge being fixed, a bridge with malthoid (slip membrane), rocker steel or concrete, and “none” would be similar in condition as a bridge with “other” bearing types. The bridges with other types of bearings are ordered in descending order of condition as follows: bridge with elastomeric bearings, bridge with pot or spherical bearings, and bridge with “other” bearing types.

5.5.8 Effect of expansion joint type on bridge deterioration

The coefficients of levels of effect of expansion joint are interpreted relative to bridges with buried under surfacing expansion joint types. The coefficients of bridges with “other” (-0.45761) and elastomeric (0.35312) are not significant i.e. bridge ASCI should be similar over time for these types of bridge as for bridges with buried under surfacing expansion joint types. The coefficient asphaltic plug (-0.74757) is negative which means that bridge ASCI should be lower over time for this type of bridge than for bridges with buried under surfacing expansion joint types. The coefficients of “none” (0.98646), thorma joint (0.8165) are positive which indicate that bridge ASCI should be higher over time for these types of bridge than for bridges with buried under surfacing expansion joint types.

With other characteristics of a bridge being fixed, a bridge with “other” expansion joint, and with elastomeric joints would be similar in condition as a bridge with buried under surfacing expansion joint. A bridge with asphaltic plug would be in a poorer condition than a bridge with buried under surfacing expansion joint. The bridges with other types of expansion joints are given in descending order of condition as follows: a bridge without expansion joint, a bridge with thorma joints bearings, and a bridge with buried under surfacing expansion joint.

5.5.9 Effect of bridge region on bridge deterioration

The coefficients of levels of effect of bridge region are interpreted relative to the Western Region. The coefficients of the Eastern Region (-0.84661) and the Northern Region (-0.62844) are negative. The negative sign means that bridge ASCI would be lower over time for bridges in these regions than for bridges in Western Region. The coefficient of the Southern region (1.27133) is positive which indicate that bridge ASCI should be higher over time for bridge in this region than for bridge in the Western Region.

With other characteristics of a bridge being equal, a bridge in the Eastern Region would be in a poorer condition than a bridge in the Northern Region, which itself would be in poorer condition than a bridge in the Western Region. A bridge in the Southern region would be in a better condition than a bridge in the Western Region.

The bridges that are located in predominantly wet and moderate regions (the Eastern Region and the Northern Region) are found to be in poorer condition except the Southern region. This may be caused by the fact that, in the wet and moderate regions, the large amount rainfall contribute negatively to the condition of bridges by causing of erosion, scour, etc. to bridge components such as piers, abutments, drainages, waterway etc. The exception of the Southern region may be a result of possible occurrence of different microclimates between the regions.

5.6 Model validation

As explained in Section 5.4, the developed model explain only 13.2 % of the variations of Bridge ASCI. On the other hand, the plotting of residuals may be used to evaluate the estimation of Bridge ASCI on different intervals. Figure 5-18 shows that the developed model is more likely to overestimate the condition for lower Bridge ASCI (Bridge ASCI < 83) whereas it is more likely to underestimate the condition for higher Bridge ASCI (Bridge ASCI > 93). Therefore, the model does not give good estimations on a large part of Bridge ASCI values.

However, the estimated regression parameters have been discussed in Section 5.5 and found, in most of the cases, to be in agreement with the results of previous studies, especially in USA (Freyermuth, et al., 1970; Tolliver & Lu, 2001). These parameters are also in accordance with the expectations with regards to the factors that influence the deterioration of bridges, precast and cast insitu deck for example. Therefore, the regression parameters may be used to compare the bridge condition index of bridges of different characteristics but may not be used to accurately predict the values of bridge condition index.

The only real validation of the deterioration model will be to test the model once a next series of inspections has been carried out. This is however a longer term exercise and not possible as part of this investigation.

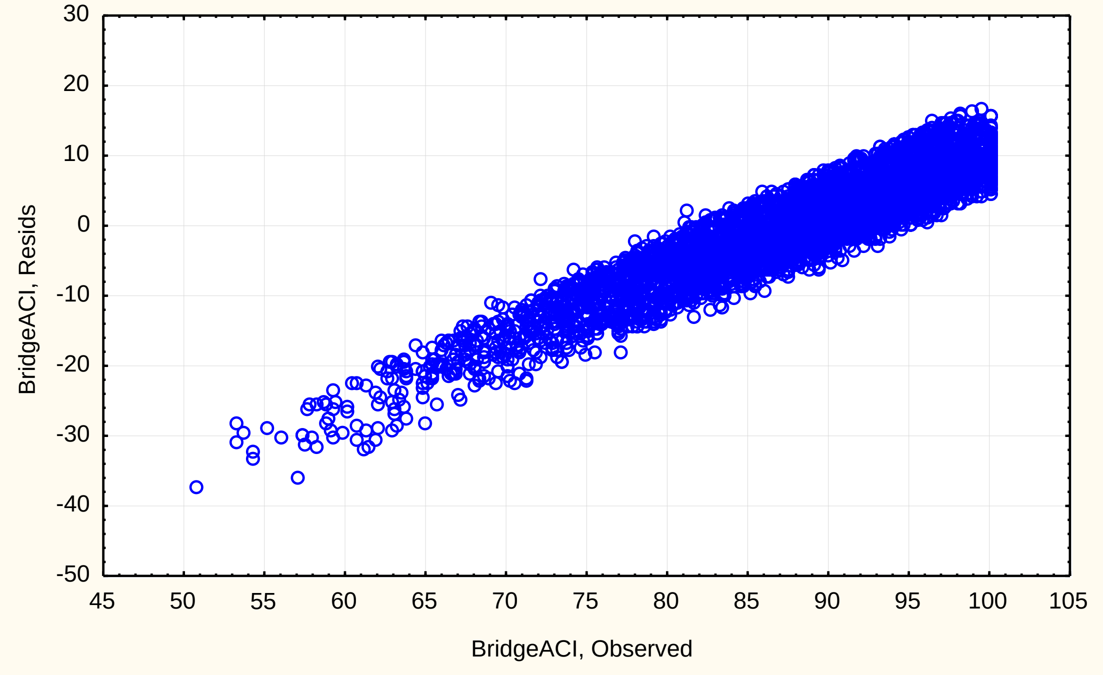


Figure 5-18 Plotting of residuals versus Bridge ASCI

5.7 Conclusion

A multiple regression analysis of bridge ASCI was carried out on data of SANRAL bridges by considering bridges characteristics that have been used as variables. All variables were found significant to bridge ASCI except the “number of spans” variable, but the correlation of the data with the estimated parameters was approximately 13.2 % i.e. regression parameters explains only 13.2 % of the variations in bridge ASCI. The cause of a low correlation is the existence of other factors that influence the deterioration of bridges that have not been included in the model due to a lack of available data. These are for example, traffic, bridge location, environment, etc. and other studies have shown the influence of these parameters on the condition of bridges.

Using regression parameters, the deterioration curve may be determined. The specific intercept changes for every category of bridge, given its characteristics whereas the rate of reduction in ASCI is the same for all bridges and depends only on the age of the bridge. The difference between time durations after which bridges of different categories reach critical level depends only on the intercept.

An example of specific intercept for a bridge category is given. The specific intercept for a simply supported river bridge in the Western region, with a cast insitu deck equipped with elastomeric bearings and asphaltic plug expansion joint is computed as $92.92827 + (-1.06838) + (-1.85062) + 0 + 0 + (1.47139) + (-0.74757) = 90.73309$. 7 terms are included in this calculation: the model intercept (92.92827), the intercept shift attributable to simply supported bridge (-1.06838), the intercept shift attributable to river bridge (-1.85062), the intercept shift attributable to the Western Region (0), the intercept shift attributable to insitu bridge (0), the intercept shift attributable to elastomeric bearings (1.47139), and the intercept shift attributable to asphaltic plug expansion joint (-0.74757). The bridge ASCI for this bridge as a function of time is therefore $\text{Bridge ASCI} = 90.73309 + (-0.09576)\, x\, t$ where t is the age of the bridge in years. For a new bridge of this category (t=0), the average of the Bridge ASCI is approximately 91.

Figure 5-19 shows examples of graphical presentation for some bridge categories.

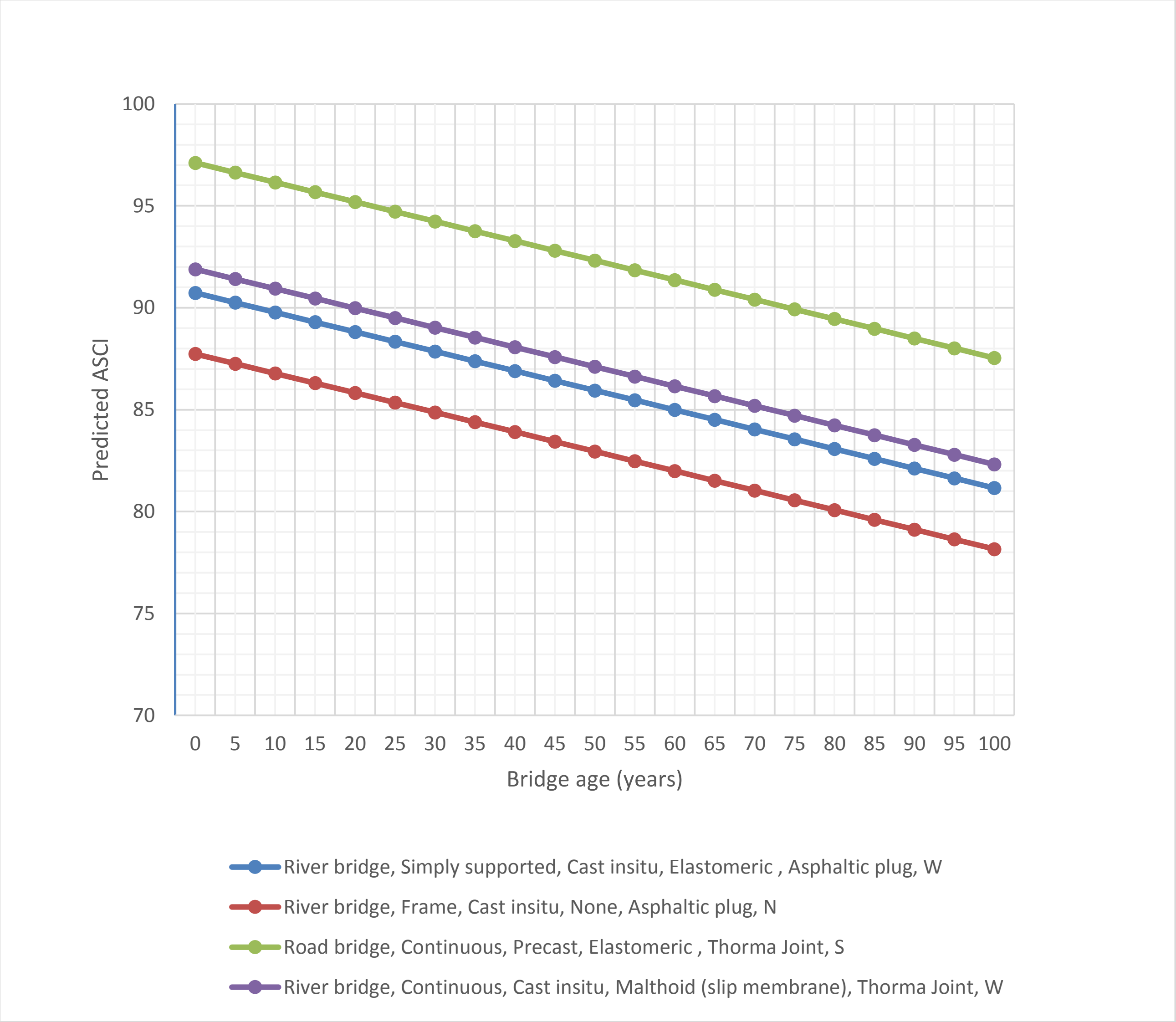


Figure 5-19. ASCI versus bridge age for some bridge categories

As shown in Figure 5-19, a bridge category with a lower intercept will reach a warning condition before a bridge category with a higher intercept. This means that the bridge category with a lower specific intercept will be in need of inspection before the bridge category with higher specific intercept. Therefore, the specific intercept may be used to rank bridge categories as a function of need of inspection.

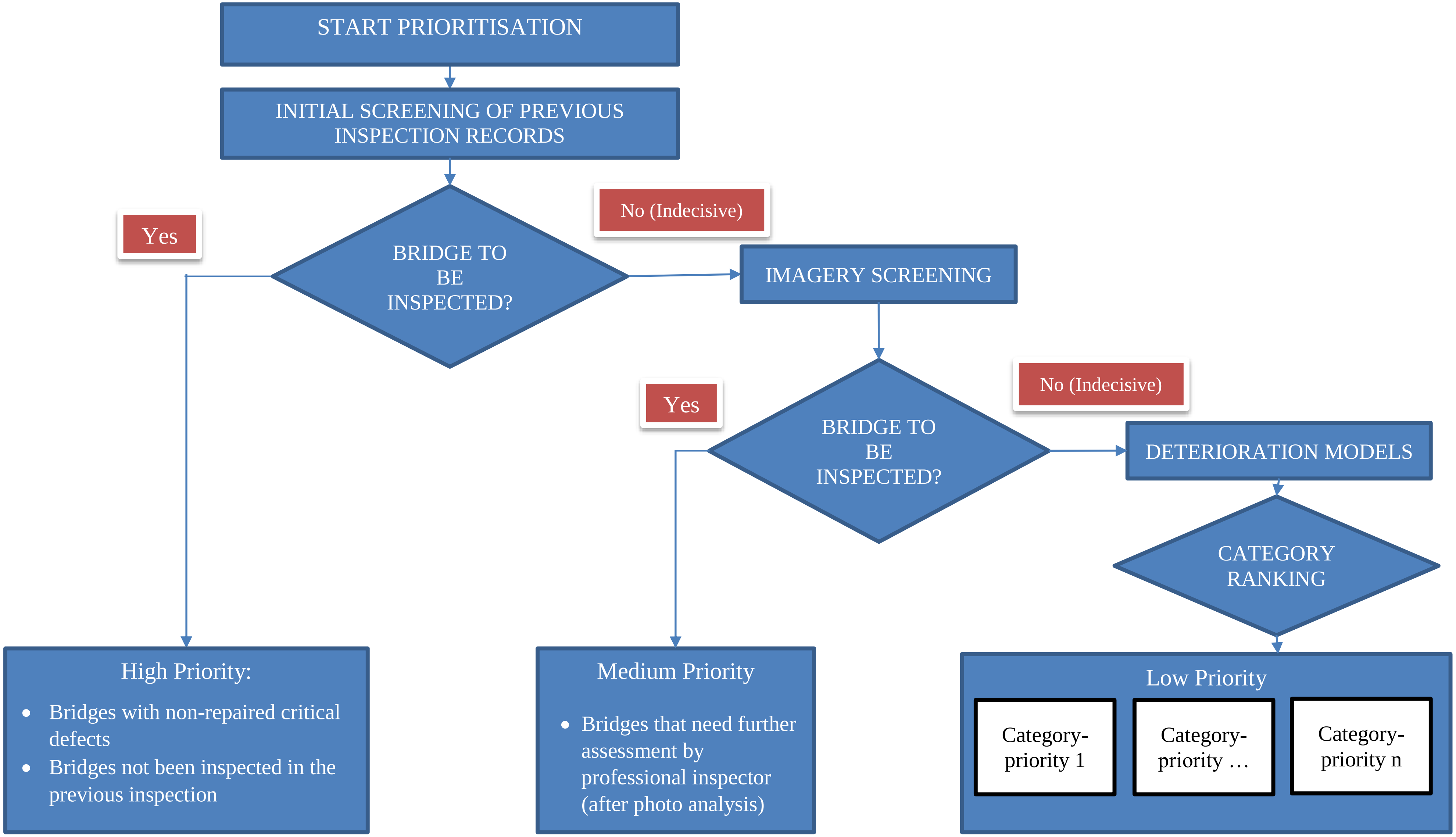
The following chapter deals with the development of bridge inspection prioritisation method that includes the use of the specific intercepts of the deterioration model to rank bridge categories for inspection. The regression parameters estimated in this chapter will be used in application of the method.

CHAPTER 6. Method for prioritisation of concrete bridge inspection

6.1 Introduction

The objective of this research is to provide a prioritisation method for concrete bridge inspection in South Africa. This method will help to plan bridge inspections by taking into account the need of specific bridges to be inspected. This method involves a combination of non-professionals, imagery inspection and bridge deterioration models. The bridge inspection prioritisation method comprises three main phases; the initial screening, imagery screening, and deterioration model based ranking. The initial screening consists of the use of the previous inspection results to identify bridges whose critical defects have not been repaired. This phase is explained in detail in Section 6.3. The identified bridges are categorised in the first priority of inspection need. The second phase is the analysis of bridge photographs taken by non-professional inspectors for defect detection. The bridges for which identified defects need further assessment by professional inspectors are placed in the second priority of inspection need. The second phase is explained in detail in Section 6.4. The third phase of this bridge inspection prioritisation method is the ranking of bridges in priority of need for inspection. This is applied to remaining bridges from the first and second phase. This ranking is based on the estimated effect of the considered variables on the bridge condition as it was determined in the Chapter 5. This phase is explained in detail in Section 6.5. Section 6.6 gives the limitation of the developed bridge inspection prioritisation method. Finally, the application of the developed prioritisation method on SANRAL's bridges is done in Section 6.7.

6.2 Layout of Bridge inspection prioritisation method



6.3 Initial screening

The first step of this bridge inspection prioritisation method is “initial screening”. The objective of this step is to identify the conditions under which the inspection of a bridge cannot be postponed, for any reason, for the scheduled inspection.

In the literature review, the hydraulic related defects were identified as the most critical defects for the failure of bridges. These defects include mainly scour and debris obstruction. Bridges in which hydraulic related defects have been identified in the previous inspections could be inspected in every following inspection until they have been repaired, in order to reduce the risk of failure related to these defects.

On the other hand, the urgency (U) rating of previous inspection recommends remedial actions to be taken for every defect. The U-rating comprises 6 ratings which are 1,2,3,4, R and 0 as defined in Table 6-1. These actions vary from *“record only”* (no action envisaged) to *“as soon as possible”* (the defect has to be fixed as soon as possible).

Some of the defects are considered to have been repaired before the scheduled inspection. These are defects with U-rating 3 (action to be taken within 5 years), 4 (defect to be repaired as soon as possible) and 4 with a “Make safe” mention (the defect receive immediate attention because it presents high risk to public safety).

To these defects are added those with a U-rating 1 as they are considered to have been repaired through routine maintenance. The survey indicated that routine maintenance activities are not the same in different road authorities. 1 ‘U-rated’ activities will thus vary by bridge authority.

Therefore, all the defects with U-rating 2 (repair action within 10 years), R (Record only = no remedial action envisaged) and 0 (Monitor only = no remedial action envisaged) are considered not to have been repaired before the scheduled inspection.

The initial screening step is intended to identify the bridges that have critical defects during the previous inspection which have not been repaired yet. This serves to assess an eventual evolution of these defects which will help to limit associated failure risks. These defects comprise all hydraulic related defects with 2, R and 0 U-ratings.

A bridge authority can identify specific critical defects that can be added to those identified in this study according to its own bridge management requirements.

Table 6-1. Urgency ratings (TMH19, 2013)

U-Rating	Description	Remarks
1	Routine	Use for remedial activities that have been identified as routine activities by the roads authority.
2	Within 10 years	With a five year inspection cycle, these are defects that only need to be repaired after the next round of principle inspections.
3	Within 5 years	These are defects that should be repaired before the next round of principle inspections.
4	As soon as possible	These are defects that should be repaired as soon as possible. In practical terms, it could take up to two years from the time that a defect is identified during an inspection until a contractor is on-site to carry out the repair. Defects where public safety risk is considered high and that have to receive immediate attention will get an urgency rating of 4, but has to be marked as a "Make Safe" item and treated accordingly.
R	Record only	This urgency rating is used for defects for which no remedial work is envisaged. Such defects would have a D-rating of 1 or 2 and an R-rating of 1.
0	Monitor only	This urgency rating is used for defects for which remedial work is not envisaged for the foreseeable future. A monitoring frequency must be indicated (e.g. 12, 24, 36 months). This urgency rating should not be used frequently, as it is not always practical for a road authority to monitor defects on structures, especially where the structures are dispersed over a wide area, as is the case for national and provincial roads authorities.

To the above identified bridges are added the bridges that have not been inspected under the previous inspection. As per discussion with a road authority agent (Roux & McDonald, 2014), in some bridge authorities, there are a number of bridges that have never been formally inspected. These are also added to the first priority category.

The bridges identified on this step are classified as high priority and have to be inspected in the following inspection i.e. their inspection cannot be postponed. The remaining bridges are subjected to imagery screening as it is explained in the following section.

6.4 Imagery screening

The bridge ASCI is calculated from average condition index of items i.e. the value of ASCI depends on the individual average indices of items. The bridge ASCI calculated from the inspection data of SANRAL bridges have been used to determine the number of the bridges for which the item index of at least one item is less than 70 i.e. the item is in a warning condition (deficient). Table 6-2 shows the number of bridges by inspection year. It is seen that, in general, more than 75 % of bridges have at least one item that is in a deficient condition (rows B).

When we consider only the bridges for which all deficient items do not have a large impact on the structural function of the bridge such as surfacing, bearings, superstructure drainage, drainage features, guardrail, curbs/sidewalks, expansion joints, waterway, parapet/handrail, and miscellaneous items; these constitute on average 40 % of the bridges having at least one deficient item as it is shown in Table 6-2 (rows C). This shows that if these bridge items are inspected by non-professional inspectors using imagery inspection, for a significant number of bridges deficient items will be identified without any need of assessment of professional inspectors.

Table 6-2. Contribution of item average condition index

Inspection year	Bridges	Number of bridges	Percentage
2005	A[1]	744	
	B[2]	573	77.0
	C[3]	362	36.8
2006	A	1675	
	B	1359	81.1
	C	766	43.6
2011	A	1666	
	B	1339	80.4
	C	775	42.1
2012	A	811	
	B	602	74.2
	C	367	39.0

1. All inspected bridges
2. Bridges with at least one deficient item
3. Bridges for which all the deficient items have no impact on structural function

In this step, photographs of defects taken after the previous inspection are analysed to identify bridges that need further inspection by professionals. The procedures and requirements of taking and sending these photographs are explained hereafter.

6.4.1 Imagery inspection by non-professionals

In this prioritisation method, the photographs of defects located on bridge items identified above are taken by non-professional inspectors and uploaded to the BMS. These photographs are then visually analysed by inspection professionals or digitally analysed by BMS software to identify bridges for which defects need further assessment by a professional inspector.

Each bridge authority can determine the defects or items to be included in this inspection process according to the capacity and the equipment that they can provide to be used in this inspection.

The defects concerned in this process are those that can be easily assessed either visually on photographs or able to be digitally processed by the BMS software where the bridge authority's BMS is able to do so. Defects such as cracks may be digitally processed as explained in Section 2.5.1 (Li et al., (2013); Abudayyeh et al., (2004)). By the digital processing, crack characteristics such as width, type, depth and length are deduced. However, as per the conducted survey, all the responding bridge authorities answered that their BMS software cannot analyse photographs for defect detection. The defect detection by BMS software processing would therefore be possible only after the upgrade of the BMS to include this feature.

For the reason above, this proposed method uses the photographs to be visually analysed by professional inspectors for defects detection or to follow up on the defects detected in previous inspections. A clear strategy with well-defined items will be needed to guide non-professionals to record the appropriate information through imagery capturing of data (see 6.4.2).

The implementation of this method requires a description of camera characteristics and non-professionals to be involved.

6.4.1.1 Camera characteristics

The quality of the photographs taken by non-professional inspectors depends on the capacity of cameras and other related equipment which in turn depends on the capacity of the bridge authority to provide such equipment. The camera used has to satisfy the following as adapted from (TMH19, 2013).

- The digital cameras are to be GPS enabled in order to facilitate attribution of the photographs to the corresponding bridge
- The cameras should have a zoom range enough to show details of the defects at a certain distance which may vary according to the defects covered by imagery inspection. For example, when cracks are among the inspected defects, the zoom range has to be high enough

for a non-professional inspector to be able to take photographs of cracks at the soffit of a high bridge.

- The cameras have to produce photographs that are clear (sharp) enough to allow a distinction of defects visually. After an eventual upgrade of the BMS, which will allow an electronic processing for detection of defects, the clearness of the taken photographs is defined by the capacity requirement of the software program.
- The focal length (how wide can the camera see): The camera would be able to take photos that permit to visualise the full extent of defects on the bridge.
- The camera should have an electronic flash for the use when a defect is in the shadow
- The camera should be equipped with a system that allows an automatic upload of photos on the BMS servers. Where it's not possible, the non-professional inspector will be equipped with a computer that he/she will use to upload the photos.

To the above characteristics, a bridge authority can add more specifications according to its needs and the conditions in which a non-professional inspection is carried out (for example, capacity of memory card (storage) for inspection in remote areas, water resistance for rainy weather, etc.)

6.4.1.2 Non-professional inspectors

As explained in the literature review, local communities may be involved in infrastructure maintenance (DFID, 2008; Bradley & Llewellyn, 2012). However, this will involve extra costs for bridge inspections as these structures are scattered over a large geographical area. These costs include training and costs of equipment that will be given to every member of the community recruited for this task, the transport and communication allowances, and administrative costs incurred to the bridge authority entity (Roux & McDonald, 2014; Rabele, 2014). The involvement of community members will also imply employment contract issues in terms of qualification requirements. A discussion with bridge authority agents (Roux & McDonald, 2014) pointed out that the involvement of a local community present risks of theft of equipment such as cameras. The authority may not be allowed to involve the 'public' as employees because of employment regulations (Roux & McDonald, 2014).

According to the survey results, 67 % of the bridge authorities have routine maintenance teams. The involvement of the members of these maintenance teams presents advantages over the involvement of local community members. Indeed, the members of maintenance teams are in active contract with the bridge authority and this will avoid a recruitment of other employees and thus reduce additional administrative, training and equipment costs. The maintenance teams may use the equipment that they use in maintenance activities such as triangles, safety jackets, signs, traffic cones, etc. In addition, no extra administration of human resources would be needed (Roux & McDonald, 2014).

Therefore, the non-professional bridge inspection preferred for this prioritisation method is the use of the members of maintenance teams. In bridge authorities where these teams do not cover the whole bridge network, the involvement of the local community members can be considered but the detailed feasibility is not covered by this research.

The training of these members of the maintenance crew will be carried out by a certified bridge inspector chosen by the bridge authority.

The extent of the bridges and the defects involved in this imagery inspection are defined by the bridge authority. The bridge items covered are those identified by the survey to be included in routine maintenance activities such as such as parapets, guardrail, approach embankments, approach embankment protection works, and deck surface. Where the equipment allows it, the inspection may be extended to other bridge items such as decks and slabs, longitudinal members and surfacing where photos of defects such as cracks and spalling can be taken.

The bridge items involved in this imagery inspection should ideally be among the routine maintenance activities in order to facilitate a smooth implementation of this inspection. According to the results of the survey, the items that are the most included in routine maintenance are: embankment protection works, approaches, drainage, parapet, wearing surface, and bearings. To this list may be added other inspection that are inspected by the routine maintenance teams such as waterway.

6.4.2 Imagery screening

The second step of this bridge inspection prioritisation method is the assessment of photographs resulting from the imagery inspection. The bridges for which detected defects at this step are judged to need assessment by professional inspectors, will be classified in the medium inspection priority category and the inspection will be conducted to assess and quantify the defects.

After this step, remaining bridges will be prioritised for inspection using deterioration models as it is detailed hereafter.

6.5 Ranking using deterioration models

Using the existing inventory and inspection data, bridge deterioration models have to be developed as it has been explained in Section 2.6.2. The choice of a suitable type of model is important and depends on many factors such as the amount of available data, the intended result and the ease or difficulty of application of the model.

The objective of the development of a deterioration model for this bridge inspection prioritisation method is to determine bridge deterioration rates as a function of their characteristics and bridge deterioration factors. These characteristics are bridge inventory information (bridge age, bridge description, bridge type, deck construction method, bearing types, expansion joint type and the number of spans, bridge location, etc.), bridge inspection information (DER ratings, item/bridge average condition index) and bridge maintenance records (rehabilitation date, retrofitting date). As identified in the literature, bridge deterioration factors such as environment (moisture, temperature effects), bridge climatic location, and traffic volume have also been found to influence bridge deterioration and are thus included in bridge deterioration models.

Deterministic regression models are easy to implement but do not take into account the uncertainties involved in bridge deterioration mechanisms. On the other hand, probabilistic models take into account the uncertainty nature of bride deterioration but require a large amount of data and specific advanced software for implementation.

To overcome these shortcomings, two types of deterioration models, a deterministic model and a stochastic model, have been chosen for this bridge inspection prioritisation method.

As explained in Section 2.6.1, deterministic models comprise mechanistic, empirical and mechanistic-empirical models. Mechanistic models are not used in infrastructure asset deterioration models as deteriorating factors cannot be explained entirely by physical laws (Ens, 2012). Empirical models, through regression, are thus suitable for these models. The deterioration model to be developed is intended to be used to determine the impact of every bridge characteristic or deteriorating factor on the condition of bridges. A multiple linear regression model where the characteristics are categorical variables are used to compare and rank the influence of bridge characteristics and deteriorating factors on bridge condition.

The estimated age parameter is used to determine the period during which a bridge deteriorates and reaches a deficient condition at which it is in need of inspection.

For the stochastic model, a binary logistic model is chosen. This deterioration model type has been chosen because of the dichotomous nature of its output. This means that the condition of a bridge may take one of two values: deficient and non-deficient. Once the level of deficiency, which is considered as the threshold of inspection need, is determined, this model will help to determine the likelihood of the bridges/items to reach this level of condition index.

As explained in Section 2.6.1, the independent variables are the powers of constants and will therefore have a multiplicative effect on the odds. This thus gives the simplest way to interpret the effect of one variable on the likelihood of deficiency when the other variables are considered fixed.

6.6 The limitations of the method

This prioritisation method has the following limitations.

- The first limitation of this method is that it cannot be applied by all bridges authorities because the initial screening is based on the U-rating which is applied only for the DER rating system. For bridge authorities where another rating system is used, the screening criteria and deterioration model's deficiency threshold will have to be defined.
- The development of the deterioration model requires a certain amount of data that should contain updated information about bridge management such as rehabilitation, retrofitting, reconstruction, etc. The use of incomplete data will therefore lead to a poor accuracy of results that may limit the extent of use of this method.
- This method cannot be applied to all types of bridges. Complex bridges such as cable stayed and suspended bridges are not applicable as their components are not easily to be subjected to imagery inspection, specifically due to the small number of such structures in South Africa.
- Without historical inspection data phase 2 is the only possible component of this method. This is because the historical inspection data plays an important role in the initial screening and deterioration models.
- The deterioration rates are considered constant over time and the same for all the bridge categories which is an approximation as, for some categories, bridges may deteriorate faster than others or the bridge category may have different deterioration rates for each lifetime period.

6.7 Application of the prioritisation method on SANRAL bridges

6.7.1 Introduction

In this section, an application of the developed prioritisation method is demonstrated on the SANRAL bridge inspections. This application is limited to two steps: the initial screening and the use of deterioration models in inspection prioritisation. For the second step, the application is limited to the specification of the imagery inspection to SANRAL.

6.7.2 Initial screening

For the application of this method, the 2011-2012 bridge inspection round was considered. The method is used to prioritise the subsequent inspection round.

The initial screening was applied to the defect ratings of the 2011-2012 inspection. This is done by ignoring the intermediate inspections.

Among available U-rating records, 2463 bridges correspond to 2011-2012 inspections. By applying the criteria of screening as explained in Section 6.3, all hydraulic related defects with 2, R and 0 U-ratings are identified on 9 bridges. Among these 9 bridges, some of them also have critical defects that are rated 3 and 4 which was supposed to be repaired before the next inspection. By supposing that, during a bridge repair programme, all the defects on a bridge are repaired, the number of bridges categorised in priority 1 reduces to 7.

To these bridges are added the bridges that have not been inspected in the round 2011-2012. The number of these bridges is 415.

The total number of bridges categorised in the first inspection priority category is then 422.

6.7.3 Imagery inspection and screening

The SANRAL routine maintenance teams are in charge of maintenance of specific highway routes. These teams are also in charge of monitoring inspection of the road and its structures including bridges. The inspection frequency is 1 year for structures (SANRAL, 2009).

For this inspection prioritisation method, the routine maintenance teams has been chosen to conduct non-professional inspection and these maintenance teams are also chosen for SANRAL for application of this prioritisation method. The camera used are chosen as explained in Section 6.4.1. The maintenance teams perform a routine monitoring of highway structures every year or after flood events. The teams report on the conditions of basic items of the structures. For this prioritisation method, photographs of identified defects will be taken during this inspection and sent (uploaded) to the SANRAL BMS. As the BMS is not able to process photographs for defects detection, the camera with same specifications as the ones defined in Section 6.4.

A capacity building program is required for routine maintenance subcontractors and/or their employees (SANRAL, 2009). The use of cameras for this prioritisation method, the upload process of these photographs, and the bridge defects to be inspected are included in the training of this building capacity program.

The list of inspection items to be included in this imagery inspection is adapted from SANRAL (2009) and the results of the conducted survey and may contain but not limited to: surfacing, bearings, approach embankment protection works, superstructure drainage, drainage features, guardrail, curbs/sidewalks, expansion joints, waterway, parapet/handrail, and miscellaneous items.

During inspection prioritisation, the photographs that have been uploaded after the previous inspection are analysed by a professional inspector for defects assessment. The defects that are judged in need of onsite inspection by professional inspectors are then classified in the priority category 2.

6.7.4 Priority categorisation using deterioration model

Using the bridge characteristics, there are 552 possible combinations of bridge region, bridge description, bridge type, deck construction method, bearing type, and expansion joint type that correspond to available bridges. For each combination, a deterioration curve may be generated as explained in Section 5.6. Some example of curves for some combinations have been shown in Figure 5-19.

The bridge characteristics are ranked based on regression parameters as shown in Table 6-3. To simplify rank calculations, the regression parameters have been grouped as follows:

- The non-significant parameters are set to 0 (parameter of dummy reference variables) as they are not significantly different from the reference
- As all the parameters are between 2 and -2, they are grouped in ranks formed from -2 and incrementing by 0.5, except of 0 that forms its own rank. 9 rank groups are thus formed.
- The rank groups are then given a number from 1 starting by the smallest group interval [-2,-1.5[i.e. -2 is included but -1.5 is not included.

Rank 1 corresponds to the high priority category and the low priority category is 9. The rank of a bridge category is calculated by summation of the individual ranking of effects. The final rank is reduced into a simple scale by subtracting from the minimal rank a number that allows to start the ranking by 1. The ranking of the first twenty combinations is shown in Table 6-4 and a cumulative number of bridges is given which can help to decide on the bridges to inspect based on the available budget. The rankings for all 552 combinations are given in Appendix 2.

Table 6-3. Ranking of parameters

Effect	Effect level	Parameter	Significant Parameters	Rank
Bridge Type	Frame	-1.96241	-1.96241	1
Bridge Description	Rail bridge	-1.85802	-1.85802	1
Bridge Description	River bridge	-1.85062	-1.85062	1
Bridge Type	Simply supported	-1.06838	-1.06838	2
Region	E	-0.84661	-0.84661	3
Expansion Joint	Asphaltic plug	-0.74757	-0.74757	3
Region	N	-0.62844	-0.62844	3
Bearing Type	Malthoid (slip membrane)	-0.62115	0	5
Expansion Joint	Other	-0.45761	0	5
Bridge Description	Pedestrian bridge	0	0	5
Bridge Type	Arch	0	0	5
Deck Construction Method	Cast insitu	0	0	5
Bearing Type	Other	0	0	5
Expansion Joint	Buried under surfacing	0	0	5
Region	W	0	0	5
Bearing Type	None	0.1442	0	5
Bridge Description	Road bridge	0.30792	0	5
Expansion Joint	Elastomeric	0.35312	0	5
Bearing Type	Rocker Steel or concrete	0.35357	0	5
Bridge Type	Continuous	0.40024	0	5
Deck Construction Method	Precast	0.62269	0.62269	7
Expansion Joint	Thorma Joint	0.8165	0.8165	7
Expansion Joint	None	0.98646	0.98646	7
Region	S	1.27133	1.27133	8
Bearing Type	Pot or Spherical	1.38974	1.38974	8
Bearing Type	Elastomeric	1.47139	1.47139	8
Bridge Type	Cellular	1.83366	1.83366	9

Table 6-4. List of the first 20 combinations

S/N	Region	Bridge Description	Bridge Type	Deck Construction Method	Bearing Type	Expansion Joint	Rank	Final rank	Number of bridges	Cumulative number of bridges
1	S	River bridge	Frame	Cast insitu	Malthoid (slip membrane)	Asphaltic plug	15	1	1	1
2	N	River bridge	Frame	Cast insitu	None	Asphaltic plug	15	1	1	2
3	E	River bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Asphaltic plug	16	2	2	4
4	N	River bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Asphaltic plug	16	2	4	8
5	S	River bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Asphaltic plug	16	2	1	9
6	W	River bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Asphaltic plug	16	2	1	10
7	N	River bridge	Simply supported	Cast insitu	Other	Asphaltic plug	16	2	1	11
8	W	River bridge	Simply supported	Cast insitu	Rocker Steel or concrete	Asphaltic plug	16	2	10	21
9	E	River bridge	Frame	Cast insitu	Malthoid (slip membrane)	Other	17	3	2	23
10	E	River bridge	Frame	Cast insitu	Malthoid (slip membrane)	Buried under surfacing	17	3	3	26
11	S	River bridge	Frame	Cast insitu	None	Other	17	3	2	28
12	E	Rail bridge	Frame	Cast insitu	None	Buried under surfacing	17	3	1	29
13	E	River bridge	Frame	Cast insitu	None	Buried under surfacing	17	3	1	30
14	N	River bridge	Frame	Cast insitu	None	Buried under surfacing	17	3	3	33
15	N	River bridge	Frame	Cast insitu	None	Elastomeric	17	3	1	34
16	E	River bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Other	18	4	3	37
17	N	River bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Other	18	4	1	38
18	S	River bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Other	18	4	1	39
19	W	River bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Other	18	4	1	40
20	E	River bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Buried under surfacing	18	4	1	41

6.7.5 Proposed inspection intervals

The development of the deterioration model has some shortcomings due to availability of data. The important missing data is the rehabilitation/reconstruction records that should help to adjust the bridge ages. This had an effect on the condition of old bridges. The other influencing factors for which the information was not available are traffic, environment, location, etc.

This is shown by the fact that for all the combinations, the ASCI does not reach the value of 70 earlier defined as the deficiency level even after a long period such as 100 years as shown in Figure 5-19. The development of a deterioration model that can accurately predict bridge ASCI was not possible as the correlation coefficient was very low (13 %). Therefore, the adjustment of the inspection interval could not be addressed.

CHAPTER 7. Conclusions and recommendations

7.1 Introduction

Bridge inspection is one of the important components of a Bridge Management System. The bridge inspection frequency defined by (TMH19, 2013) is not respected in some bridge authorities in South Africa. The main objective of this research is to provide a bridge inspection prioritisation method that involves non-professional inspectors, imagery inspection and deterioration modelling. During the study, a survey has been conducted amongst some bridge authorities in order to obtain updated information on South African inspection practices. Inventory and inspection data of bridges managed by SANRAL have been used to develop a multiple linear regression model. The survey information, together with a literature review and a regression model, were used to develop a prioritisation method for bridge inspection in South Africa. This chapter gives the conclusions and recommendations for application and further studies.

7.2 Conclusions

Through the survey that has been conducted amongst South African bridge authorities that use STRUMAN BMS software, it was found that the inspection frequency of 5 years required by TMH19 (2013) is not respected in some bridge authorities. This is due, in general, to a lack of funds and personnel. This survey also confirmed a systematic inspection in bridge authorities with enough inspection funds or limited number of bridges to be inspected. These findings support the need of a bridge inspection prioritisation method that takes into account bridge need of inspection.

A bridge inspection prioritisation method has been developed and applied to SANRAL bridges. The method comprises three phases: initial screening, imagery based screening, and categorisation ranking of bridges based on deterioration model. These phases consist of grouping of bridges into priority categorisation by taking into account their need of inspection.

The initial screen is an identification of bridges with critical defects that have not been repaired. These bridges are identified using records of previous inspections. The critical defects have been identified from literature as the hydraulic related defects.

The imagery based screening consists of identification of bridges with defects that need an urgent assessment by a professional inspector. This identification is carried out using digital photographs taken by non-professional inspectors and uploaded to the BMS. The maintenance team members were found to be the most appropriate to be involved as non-professional inspectors for this bridge inspection prioritisation method. This is because routine maintenance teams are already contracted with bridge authorities and their involvement does not involve supplementary costs in terms of equipment and administration. The maintenance teams are also involved in routine monitoring and the survey identified them as the main informal source of information about bridge condition. The use of a digital camera in bridge inspection is also a common practice in bridge authorities but is limited to reporting and archival purposes. The criteria used to define the specifications of a digital camera to be used were identified and depend on whether the photographs are examined by inspectors or are digitally processed. From this, it was found that the integration of non-professional inspectors and imagery inspection in the prioritisation method of bridge inspection is easy as it would be an improvement of existing inspection practices.

The third phase consist of a ranking of bridge categories as a function of their need for inspection using the regression parameters of the deterioration model. Based on the advantages and disadvantages of deterioration model types, multiple linear regression and logistic binary regression of Bridge ASCI on independent variables were found to be appropriate for this bridge inspection prioritisation method. These deterioration models should consider regression variables such as bridge inventory information, bridge inspection records and other bridge deterioration factors identified in the literature such as environment, climatic location, and traffic volume.

The method was then applied to SANRAL bridges. Combining the identification of critical defects and the bridge urgency rating, 7 bridges in need of inspection were identified for the first priority ranking. To these bridges are added the bridges that have not been inspected in the round 2011-2012. The number of these bridges is 415.

For the imagery screening phase, the study was limited to the definition of the requirements for application of this phase.

The available data was used to develop a multiple linear regression model by including bridge region, bridge description, bridge type, deck construction method, bearing type, and expansion joint type as variables. The multiple linear regression model was chosen to be appropriate for SANRAL bridges because the dependent variable (Bridge ASCI) is continuous. These variables were significant but with a low correlation coefficient (13.2 %) which was caused by a lack of information about factors that influence bridge deterioration such as traffic volumes, and rehabilitation records. The analysis of residuals indicated that the model does not give good estimations on all intervals of Bridge ASCI values. However, the estimated regression parameters were found to be in agreement with the results of previous studies. Therefore the regression parameters were used to demonstrate the prioritisation method and 522 possible combinations have been ranked where the lower the rank, the higher is the inspection priority.

7.3 Limitations

The bridge inspection prioritisation method was developed and has been applied to SANRAL bridges. This method permitted a ranking of bridges as a function of the need of inspection. However this method has the following limitations.

- The inspection and inventory data that has been used does not contain rehabilitation records. The adjustment of bridge age by considering renewal or reconstruction date could not be done and a number of bridges were considered to be older than they really are.
- More information that could improve the output and the fitting of a deterioration model to actual data was not available. These are traffic volumes, environment to which bridges are exposed, and geographic location. As it has been highlighted by the literature, these factors have been determined to influence the deterioration of bridges and thus, their availability could improve the regression results and permit to adjust inspection intervals i.e. determine bridge categories for which inspection interval may be increased or has to be reduced.

7.4 Recommendations

Based on the objectives of the research, the conclusions and the limitations, the following recommendations are given:

- The developed prioritisation method was used to categorise bridges in inspection priority order. Bridge authorities that cannot respect the inspection frequency can apply this method to choose the number of bridges to inspect by taking into account the available budget.
- The first phase of the developed prioritisation method is the identification of bridges with a history of critical defects. More research could be done to identify bridge critical defects in South Africa so that they can be included in the method.
- The survey results show that STRUMAN BMS is not able to detect defects such as cracks and spalling by digital photograph processing. Therefore, the application of this method necessitates more research on upgrading of BMS to include this capacity.
- Including rehabilitation records in the BMS database is necessary to permit an accurate and updated inventory data especially for the reconstruction, rehabilitation and retrofitting records.
- The development of deterioration models that includes the factors that were not available for this research is recommended for further studies. This will lead to a better understanding of the bridge deteriorating factors in South Africa and more accuracy in bridge condition prediction and inspection need evaluation.

- The bridge inspection prioritisation method developed in this research did not consider the costs of repair. It is recommended for further research to include the cost of repair as a variable for prioritisation of bridge inspections.

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Appendices

Appendix 1: Survey questionnaire

Introductory letter

Dear Sir/ Madam,

I am performing research for a Master of Engineering in the division of Construction Engineering and Management of the Department of Civil Engineering at Stellenbosch University. The topic of my research is “Prioritisation of concrete bridge inspections by integration of community imagery inspection”

For the purpose of this topic, I need to investigate the following:

- The current practice of concrete bridge inspections;
- The use of information about bridge condition inspections from informal sources.

The research aims to propose a method to prioritise bridge inspections in South Africa.

I would like to invite you to participate in this study and would appreciate your feedback on a questionnaire. It shouldn’t take more than 10 minutes of your time to complete as it is mainly based on making appropriate choices from potential answers.

Participation in the study is voluntary and you are free to withdraw at any time. All the information would be treated in strict confidence and data will be used for academic purposes only. Individuals and agencies will not be identified in the research results.

Your participation will help to obtain an overview of the current situation of bridge inspections in South Africa. The result of the research would be available to share with the participants upon request.

The research is led by Prof. Jan Wium who can be reached for further information at: janw@sun.ac.sa or +27 21 808 4348.

I sincerely thank you for your cooperation.

Faithfully yours,

Placide Nsabimana

Cellphone: +27 71 927 1414

Email: 16841336@sun.ac.sa

Stellenbosch University

PRIORITISATION OF CONCRETE BRIDGES INSPECTION BY INTEGRATION OF COMMUNITY IMAGERY INSPECTION

QUESTIONNAIRE:

1. Respondent details:

1.1. Bridge (roads) authority:

a. National ☐

b. Provincial ☐

c. Municipal ☐

1.2. Bridge authority name ………………

2. Inventory

2.1. Number of bridges (depending on available records)

Year	1980-1984	1985-1999	2000-2004	2005-2009	2010-2014
Number of bridges					
Inspected bridges (number / percentage)					

2.2. Obstacle crossed

Crossed obstacle	Number
Road over road/railway	
Road over **r**iver	

3. Inspection

3.1. What is your bridge inspection condition rating scale?

0(No defect) - 4(severe) ☐

0(Failed) - 9(excellent) ☐

Other (please specify) ………………….

3.2. Does your bridge authority have its own inspection regulation (standards, procedures, manuals, guidelines)?

Yes ☐

No ☐

If yes, please give the name (s) of the document: ……………………………………..
If no, please specify which document is used: ……………………………………

3.3. What is the frequency of bridge inspection as provided by regulations?

Biannually ☐

Annually ☐

Every Two Years ☐

Every Three Years ☐

Every Four Years ☐

Every Five Years ☐
Other (please specify) ………………………

3.4. Is the bridge inspection frequency respected as required in regulations?

Yes ☐

No ☐

If no. This is because of: Lack of funds ☐

Lack of personnel ☐

Another reason (please specify) ……………

3.5. Is inspection prioritised based on defined criteria?

Yes ☐

No (randomly) ☐

Bridges are inspected systematically ☐

3.6. If the inspection is prioritised, what is the tool used?

N°	Used tool	Yes	No
1	Deterioration models		
2	Risk-based approach		
3	BMS software		
4	Other (specify)		
5			

3.7. Who does inspection?

N°	Bridge inspector	Yes	No	Number of bridges (%)
1	Private consultant			
2	Authority's personnel			

4. Informal Inspections

4.1. Do you collect information on bridge conditions from third party?

N°	Informal source	Yes	No
1	Police patrol		
2	Road maintenance crew		
3	Anonymous call		
4	Other (specify) ……………………..		

4.2. Do you record information collected from informal sources?

N°	Record	Yes	No
1	BMS		
2	Bridge file		
3	Other (specify)		

4.3. Do you use information collected from informal sources?

N°	Use of informal information	Yes	No
1	Inspection prioritisation		
2	Bridge maintenance		
3	Other (specify) ……………………………		

5. Imagery inspection

5.1. Do you use digital cameras in bridge inspection?

Yes ☐
No ☐

5.2. Are taken photos uploaded on the BMS?

Yes ☐
No ☐

5.3. Can the BMS analyse the photos for defects detection?

Yes ☐
No ☐

6. Maintenance

6.1. Do you have a routine maintenance program?

Yes ☐
No ☐

6.2. If yes. What are its activities?

N°	Activity	Yes	No
1	Drainage cleaning		
2	Joints cleaning		
3	Bearing cleaning		
4	Parapet cleaning (repair)		
5	Wearing surface minor repairs		
6	Correcting erosion problems		
7	Stabilising banks		
8	Debris removal		

6.3. Who does routine maintenance activities?

N°	Maintenance team	Yes	No	Number of bridges (%)
1	Private company			
2	Authority’s personnel			

Appendix 2 Ranking of bridge categories based on the deterioration model

S/N	Region	Bridge Description	Bridge Type	Deck Construction Method	Bearing Type	Expansion Joint	Rank	Final rank	Number of bridges	Cumulative number of bridges
1	S	River bridge	Frame	Cast insitu	Malthoid (slip membrane)	Asphaltic plug	15	1	1	1
2	N	River bridge	Frame	Cast insitu	None	Asphaltic plug	15	1	1	2
3	E	River bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Asphaltic plug	16	2	2	4
4	N	River bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Asphaltic plug	16	2	4	8
5	S	River bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Asphaltic plug	16	2	1	9
6	W	River bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Asphaltic plug	16	2	1	10
7	N	River bridge	Simply supported	Cast insitu	Other	Asphaltic plug	16	2	1	11
8	W	River bridge	Simply supported	Cast insitu	Rocker Steel or concrete	Asphaltic plug	16	2	10	21
9	E	River bridge	Frame	Cast insitu	Malthoid (slip membrane)	Other	17	3	2	23
10	E	River bridge	Frame	Cast insitu	Malthoid (slip membrane)	Buried under surfacing	17	3	3	26
11	S	River bridge	Frame	Cast insitu	None	Other	17	3	2	28
12	E	Rail bridge	Frame	Cast insitu	None	Buried under surfacing	17	3	1	29
13	E	River bridge	Frame	Cast insitu	None	Buried under surfacing	17	3	1	30
14	N	River bridge	Frame	Cast insitu	None	Buried under surfacing	17	3	3	33
15	N	River bridge	Frame	Cast insitu	None	Elastomeric	17	3	1	34
16	E	River bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Other	18	4	3	37
17	N	River bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Other	18	4	1	38
18	S	River bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Other	18	4	1	39
19	W	River bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Other	18	4	1	40
20	E	River bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Buried under surfacing	18	4	1	41
21	E	River bridge	Simply supported	Precast	Malthoid (slip membrane)	Asphaltic plug	18	4	5	46
22	N	River bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Buried under surfacing	18	4	1	47
23	N	River bridge	Simply supported	Precast	Malthoid (slip membrane)	Asphaltic plug	18	4	1	48
24	S	River bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Buried under surfacing	18	4	1	49
25	W	Rail bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Buried under surfacing	18	4	1	50
26	W	River bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Buried under surfacing	18	4	7	57
27	N	River bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Elastomeric	18	4	4	61
28	N	River bridge	Simply supported	Cast insitu	Other	Other	18	4	2	63
29	S	River bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Elastomeric	18	4	1	64
30	W	River bridge	Simply supported	Cast insitu	Other	Other	18	4	1	65
31	E	River bridge	Simply supported	Cast insitu	Other	Buried under surfacing	18	4	2	67
32	N	Rail bridge	Simply supported	Cast insitu	Other	Buried under surfacing	18	4	1	68
33	N	River bridge	Simply supported	Cast insitu	Other	Buried under surfacing	18	4	21	89
34	N	River bridge	Simply supported	Cast insitu	Rocker Steel or concrete	Other	18	4	3	92
35	S	River bridge	Simply supported	Cast insitu	Rocker Steel or concrete	Other	18	4	5	97
36	E	Rail bridge	Simply supported	Precast	Rocker Steel or concrete	Asphaltic plug	18	4	1	98
37	E	River bridge	Simply supported	Precast	Rocker Steel or concrete	Asphaltic plug	18	4	4	102
38	N	River bridge	Simply supported	Cast insitu	Rocker Steel or concrete	Buried under surfacing	18	4	2	104

S/N	Region	Bridge Description	Bridge Type	Deck Construction Method	Bearing Type	Expansion Joint	Rank	Final rank	Number of bridges	Cumulative number of bridges
39	W	River bridge	Simply supported	Cast insitu	Rocker Steel or concrete	Buried under surfacing	18	4	1	105
40	N	River bridge	Simply supported	Cast insitu	Rocker Steel or concrete	Elastomeric	18	4	3	108
41	N	River bridge	Frame	Cast insitu	Malthoid (slip membrane)	None	19	5	1	109
42	E	River bridge	Continuous	Cast insitu	Malthoid (slip membrane)	Asphaltic plug	19	5	9	118
43	N	River bridge	Continuous	Cast insitu	Malthoid (slip membrane)	Asphaltic plug	19	5	1	119
44	W	River bridge	Continuous	Cast insitu	Malthoid (slip membrane)	Asphaltic plug	19	5	1	120
45	E	River bridge	Simply supported	Cast insitu	Elastomeric	Asphaltic plug	19	5	1	121
46	E	River bridge	Simply supported	Cast insitu	Pot or Spherical	Asphaltic plug	19	5	1	122
47	N	River bridge	Simply supported	Cast insitu	Elastomeric	Asphaltic plug	19	5	1	123
48	S	River bridge	Simply supported	Cast insitu	Elastomeric	Asphaltic plug	19	5	5	128
49	W	River bridge	Simply supported	Cast insitu	Elastomeric	Asphaltic plug	19	5	11	139
50	E	River bridge	Continuous	Cast insitu	Other	Asphaltic plug	19	5	10	149
51	N	Rail bridge	Frame	Cast insitu	None	None	19	5	3	152
52	S	River bridge	Frame	Cast insitu	None	Thorma Joint	19	5	1	153
53	W	River bridge	Continuous	Cast insitu	Other	Asphaltic plug	19	5	13	166
54	E	River bridge	Continuous	Cast insitu	None	Asphaltic plug	19	5	2	168
55	E	Road bridge	Frame	Cast insitu	None	Asphaltic plug	19	5	9	177
56	N	River bridge	Continuous	Cast insitu	None	Asphaltic plug	19	5	91	268
57	N	Road bridge	Frame	Cast insitu	None	Asphaltic plug	19	5	28	296
58	S	Road bridge	Frame	Cast insitu	None	Asphaltic plug	19	5	19	315
59	W	Road bridge	Frame	Cast insitu	None	Asphaltic plug	19	5	5	320
60	N	River bridge	Simply supported	Precast	Malthoid (slip membrane)	Other	20	6	4	324
61	E	Rail bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	None	20	6	1	325
62	E	Rail bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Thorma Joint	20	6	1	326
63	E	River bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	None	20	6	1	327
64	E	River bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Thorma Joint	20	6	1	328
65	E	River bridge	Simply supported	Precast	Malthoid (slip membrane)	Buried under surfacing	20	6	8	336
66	N	River bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	None	20	6	2	338
67	N	River bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Thorma Joint	20	6	7	345
68	N	River bridge	Simply supported	Precast	Malthoid (slip membrane)	Buried under surfacing	20	6	3	348
69	S	River bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	None	20	6	1	349
70	S	River bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Thorma Joint	20	6	2	351
71	W	River bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Thorma Joint	20	6	2	353
72	E	River bridge	Simply supported	Precast	Other	Other	20	6	4	357
73	E	Road bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Asphaltic plug	20	6	1	358
74	N	River bridge	Simply supported	Precast	Other	Other	20	6	2	360
75	N	Road bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Asphaltic plug	20	6	1	361
76	S	Road bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Asphaltic plug	20	6	1	362

S/N	Region	Bridge Description	Bridge Type	Deck Construction Method	Bearing Type	Expansion Joint	Rank	Final rank	Number of bridges	Cumulative number of bridges
77	W	Road bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Asphaltic plug	20	6	1	363
78	E	River bridge	Simply supported	Cast insitu	Other	Thorma Joint	20	6	1	364
79	N	River bridge	Simply supported	Precast	Rocker Steel or concrete	Other	20	6	1	365
80	S	River bridge	Simply supported	Precast	Rocker Steel or concrete	Other	20	6	1	366
81	N	River bridge	Simply supported	Cast insitu	None	None	20	6	7	373
82	N	River bridge	Simply supported	Cast insitu	Rocker Steel or concrete	Thorma Joint	20	6	2	375
83	N	River bridge	Simply supported	Precast	Other	Elastomeric	20	6	6	381
84	W	River bridge	Simply supported	Cast insitu	Rocker Steel or concrete	Thorma Joint	20	6	17	398
85	E	Road bridge	Simply supported	Cast insitu	None	Asphaltic plug	20	6	2	400
86	N	River bridge	Simply supported	Precast	Rocker Steel or concrete	Elastomeric	20	6	1	401
87	S	River bridge	Simply supported	Precast	None	Elastomeric	20	6	2	403
88	S	River bridge	Simply supported	Precast	Rocker Steel or concrete	Elastomeric	20	6	1	404
89	W	Road bridge	Simply supported	Cast insitu	None	Asphaltic plug	20	6	2	406
90	S	Pedestrian bridge	Frame	Cast insitu	Malthoid (slip membrane)	Other	21	7	1	407
91	E	River bridge	Arch	Cast insitu	Malthoid (slip membrane)	Buried under surfacing	21	7	1	408
92	E	River bridge	Continuous	Cast insitu	Malthoid (slip membrane)	Other	21	7	1	409
93	N	Rail bridge	Continuous	Cast insitu	Malthoid (slip membrane)	Other	21	7	3	412
94	N	River bridge	Continuous	Cast insitu	Malthoid (slip membrane)	Other	21	7	1	413
95	S	River bridge	Continuous	Cast insitu	Malthoid (slip membrane)	Other	21	7	2	415
96	W	River bridge	Arch	Cast insitu	Malthoid (slip membrane)	Buried under surfacing	21	7	2	417
97	E	Rail bridge	Simply supported	Cast insitu	Pot or Spherical	Other	21	7	1	418
98	E	River bridge	Continuous	Cast insitu	Malthoid (slip membrane)	Buried under surfacing	21	7	3	421
99	E	River bridge	Simply supported	Cast insitu	Elastomeric	Other	21	7	15	436
100	E	River bridge	Simply supported	Cast insitu	Pot or Spherical	Other	21	7	5	441
101	N	Rail bridge	Continuous	Cast insitu	Malthoid (slip membrane)	Buried under surfacing	21	7	21	462
102	N	Rail bridge	Simply supported	Cast insitu	Pot or Spherical	Other	21	7	81	543
103	N	River bridge	Continuous	Cast insitu	Malthoid (slip membrane)	Buried under surfacing	21	7	1	544
104	N	River bridge	Continuous	Precast	Malthoid (slip membrane)	Asphaltic plug	21	7	3	547
105	N	River bridge	Simply supported	Cast insitu	Elastomeric	Other	21	7	2	549
106	N	River bridge	Simply supported	Cast insitu	Pot or Spherical	Other	21	7	3	552
107	S	River bridge	Continuous	Cast insitu	Malthoid (slip membrane)	Buried under surfacing	21	7	2	554
108	S	River bridge	Simply supported	Cast insitu	Elastomeric	Other	21	7	1	555
109	W	River bridge	Continuous	Cast insitu	Malthoid (slip membrane)	Buried under surfacing	21	7	20	575
110	W	River bridge	Simply supported	Cast insitu	Elastomeric	Other	21	7	7	582
111	E	River bridge	Arch	Cast insitu	Rocker Steel or concrete	Other	21	7	4	586
112	E	River bridge	Simply supported	Cast insitu	Elastomeric	Buried under surfacing	21	7	2	588
113	E	River bridge	Simply supported	Precast	Elastomeric	Asphaltic plug	21	7	18	606
114	N	Rail bridge	Simply supported	Cast insitu	Elastomeric	Buried under surfacing	21	7	2	608

S/N	Region	Bridge Description	Bridge Type	Deck Construction Method	Bearing Type	Expansion Joint	Rank	Final rank	Number of bridges	Cumulative number of bridges
115	N	Rail bridge	Simply supported	Precast	Elastomeric	Asphaltic plug	21	7	2	610
116	N	River bridge	Arch	Cast insitu	Other	Buried under surfacing	21	7	16	626
117	N	River bridge	Continuous	Cast insitu	Malthoid (slip membrane)	Elastomeric	21	7	3	629
118	N	River bridge	Continuous	Cast insitu	Other	Other	21	7	3	632
119	N	River bridge	Simply supported	Cast insitu	Elastomeric	Buried under surfacing	21	7	9	641
120	N	River bridge	Simply supported	Cast insitu	Pot or Spherical	Buried under surfacing	21	7	5	646
121	N	River bridge	Simply supported	Precast	Elastomeric	Asphaltic plug	21	7	1	647
122	N	Road bridge	Frame	Cast insitu	Malthoid (slip membrane)	Elastomeric	21	7	1	648
123	S	River bridge	Simply supported	Precast	Elastomeric	Asphaltic plug	21	7	1	649
124	W	Rail bridge	Simply supported	Precast	Elastomeric	Asphaltic plug	21	7	1	650
125	W	River bridge	Simply supported	Cast insitu	Elastomeric	Buried under surfacing	21	7	1	651
126	W	River bridge	Simply supported	Cast insitu	Pot or Spherical	Buried under surfacing	21	7	1	652
127	W	River bridge	Simply supported	Precast	Elastomeric	Asphaltic plug	21	7	1	653
128	E	River bridge	Arch	Cast insitu	None	Buried under surfacing	21	7	2	655
129	E	River bridge	Continuous	Cast insitu	None	Other	21	7	1	656
130	E	River bridge	Simply supported	Cast insitu	Elastomeric	Elastomeric	21	7	3	659
131	E	Road bridge	Frame	Cast insitu	Other	Buried under surfacing	21	7	3	662
132	N	Rail bridge	Simply supported	Cast insitu	Pot or Spherical	Elastomeric	21	7	7	669
133	N	River bridge	Arch	Cast insitu	None	Buried under surfacing	21	7	1	670
134	N	River bridge	Continuous	Cast insitu	None	Other	21	7	3	673
135	N	River bridge	Continuous	Cast insitu	Other	Buried under surfacing	21	7	3	676
136	N	River bridge	Frame	Precast	None	None	21	7	2	678
137	N	River bridge	Simply supported	Cast insitu	Elastomeric	Elastomeric	21	7	1	679
138	N	River bridge	Simply supported	Cast insitu	Pot or Spherical	Elastomeric	21	7	2	681
139	N	Road bridge	Frame	Cast insitu	None	Other	21	7	1	682
140	N	Road bridge	Frame	Cast insitu	Other	Buried under surfacing	21	7	1	683
141	S	River bridge	Simply supported	Cast insitu	Pot or Spherical	Elastomeric	21	7	1	684
142	S	Road bridge	Frame	Cast insitu	None	Other	21	7	2	686
143	W	River bridge	Simply supported	Cast insitu	Elastomeric	Elastomeric	21	7	1	687
144	W	Road bridge	Frame	Cast insitu	Other	Buried under surfacing	21	7	2	689
145	E	Road bridge	Frame	Cast insitu	Other	Elastomeric	21	7	1	690
146	N	River bridge	Continuous	Cast insitu	None	Buried under surfacing	21	7	3	693
147	N	Road bridge	Frame	Cast insitu	None	Buried under surfacing	21	7	1	694
148	S	Road bridge	Frame	Cast insitu	None	Buried under surfacing	21	7	1	695
149	W	Road bridge	Frame	Cast insitu	None	Elastomeric	21	7	5	700
150	E	Road bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Other	22	8	2	702
151	N	River bridge	Simply supported	Precast	Malthoid (slip membrane)	Thorma Joint	22	8	1	703
152	N	Road bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Other	22	8	2	705

S/N	Region	Bridge Description	Bridge Type	Deck Construction Method	Bearing Type	Expansion Joint	Rank	Final rank	Number of bridges	Cumulative number of bridges
153	S	River bridge	Simply supported	Precast	Malthoid (slip membrane)	None	22	8	1	706
154	S	River bridge	Simply supported	Precast	Malthoid (slip membrane)	Thorma Joint	22	8	1	707
155	S	Road bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Other	22	8	1	708
156	E	Rail bridge	Simply supported	Cast insitu	Concrete Hinge and Pad	Other	22	8	2	710
157	E	Road bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Buried under surfacing	22	8	6	716
158	E	Road bridge	Simply supported	Precast	Malthoid (slip membrane)	Asphaltic plug	22	8	1	717
159	N	River bridge	Simply supported	Cast insitu	Roller	Other	22	8	5	722
160	N	Road bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Buried under surfacing	22	8	1	723
161	N	Road bridge	Simply supported	Precast	Malthoid (slip membrane)	Asphaltic plug	22	8	6	729
162	S	Road bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Buried under surfacing	22	8	1	730
163	S	Road bridge	Simply supported	Precast	Malthoid (slip membrane)	Asphaltic plug	22	8	1	731
164	W	Road bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Buried under surfacing	22	8	2	733
165	W	Road bridge	Simply supported	Precast	Malthoid (slip membrane)	Asphaltic plug	22	8	1	734
166	E	River bridge	Simply supported	Precast	Other	Thorma Joint	22	8	1	735
167	E	Road bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Elastomeric	22	8	1	736
168	N	Road bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Elastomeric	22	8	3	739
169	N	Road bridge	Simply supported	Cast insitu	Other	Other	22	8	2	741
170	S	Road bridge	Simply supported	Cast insitu	Other	Other	22	8	1	742
171	W	Road bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Elastomeric	22	8	2	744
172	E	River bridge	Continuous	Cast insitu	Elastomeric	Asphaltic plug	22	8	8	752
173	E	Road bridge	Simply supported	Cast insitu	Other	Buried under surfacing	22	8	1	753
174	N	Rail bridge	Simply supported	Precast	Rocker Steel or concrete	Thorma Joint	22	8	1	754
175	N	River bridge	Continuous	Cast insitu	Elastomeric	Asphaltic plug	22	8	1	755
176	N	Road bridge	Simply supported	Cast insitu	Other	Buried under surfacing	22	8	1	756
177	N	Road bridge	Simply supported	Precast	Other	Asphaltic plug	22	8	1	757
178	S	Road bridge	Simply supported	Cast insitu	Other	Buried under surfacing	22	8	1	758
179	E	Road bridge	Simply supported	Cast insitu	None	Buried under surfacing	22	8	2	760
180	E	Road bridge	Simply supported	Cast insitu	Other	Elastomeric	22	8	1	761
181	E	Road bridge	Simply supported	Precast	Rocker Steel or concrete	Asphaltic plug	22	8	4	765
182	N	Road bridge	Simply supported	Cast insitu	None	Buried under surfacing	22	8	2	767
183	W	Road bridge	Simply supported	Precast	Rocker Steel or concrete	Asphaltic plug	22	8	1	768
184	E	Road bridge	Simply supported	Cast insitu	None	Elastomeric	22	8	1	769
185	W	Road bridge	Simply supported	Cast insitu	None	Elastomeric	22	8	1	770
186	E	River bridge	Arch	Cast insitu	Malthoid (slip membrane)	None	23	9	7	777
187	E	River bridge	Cellular	Cast insitu	Malthoid (slip membrane)	Asphaltic plug	23	9	1	778
188	N	Pedestrian bridge	Frame	Precast	Malthoid (slip membrane)	Buried under surfacing	23	9	4	782
189	N	River bridge	Continuous	Precast	Malthoid (slip membrane)	Other	23	9	1	783
190	E	River bridge	Continuous	Cast insitu	Malthoid (slip membrane)	None	23	9	1	784

S/N	Region	Bridge Description	Bridge Type	Deck Construction Method	Bearing Type	Expansion Joint	Rank	Final rank	Number of bridges	Cumulative number of bridges
191	E	River bridge	Simply supported	Precast	Elastomeric	Other	23	9	1	785
192	E	River bridge	Simply supported	Precast	Pot or Spherical	Other	23	9	1	786
193	N	Rail bridge	Simply supported	Precast	Elastomeric	Other	23	9	2	788
194	N	River bridge	Continuous	Cast insitu	Malthoid (slip membrane)	None	23	9	5	793
195	N	River bridge	Continuous	Cast insitu	Malthoid (slip membrane)	Thorma Joint	23	9	17	810
196	N	River bridge	Simply supported	Precast	Elastomeric	Other	23	9	1	811
197	N	River bridge	Simply supported	Precast	Pot or Spherical	Other	23	9	3	814
198	N	Road bridge	Frame	Cast insitu	Malthoid (slip membrane)	None	23	9	1	815
199	S	River bridge	Continuous	Cast insitu	Malthoid (slip membrane)	None	23	9	2	817
200	S	River bridge	Simply supported	Precast	Elastomeric	Other	23	9	2	819
201	S	River bridge	Simply supported	Precast	Pot or Spherical	Other	23	9	23	842
202	S	Road bridge	Frame	Cast insitu	Malthoid (slip membrane)	None	23	9	1	843
203	W	River bridge	Continuous	Cast insitu	Malthoid (slip membrane)	Thorma Joint	23	9	1	844
204	W	River bridge	Simply supported	Precast	Elastomeric	Other	23	9	13	857
205	E	River bridge	Simply supported	Cast insitu	Elastomeric	None	23	9	2	859
206	E	River bridge	Simply supported	Cast insitu	Elastomeric	Thorma Joint	23	9	10	869
207	E	River bridge	Simply supported	Precast	Elastomeric	Buried under surfacing	23	9	2	871
208	E	Road bridge	Continuous	Cast insitu	Malthoid (slip membrane)	Asphaltic plug	23	9	3	874
209	N	Rail bridge	Simply supported	Cast insitu	Elastomeric	None	23	9	2	876
210	N	River bridge	Simply supported	Cast insitu	Elastomeric	None	23	9	7	883
211	N	River bridge	Simply supported	Cast insitu	Elastomeric	Thorma Joint	23	9	5	888
212	N	River bridge	Simply supported	Cast insitu	Pot or Spherical	Thorma Joint	23	9	19	907
213	N	River bridge	Simply supported	Precast	Elastomeric	Buried under surfacing	23	9	43	950
214	N	River bridge	Simply supported	Precast	Pot or Spherical	Buried under surfacing	23	9	2	952
215	N	Road bridge	Continuous	Cast insitu	Malthoid (slip membrane)	Asphaltic plug	23	9	17	969
216	S	River bridge	Simply supported	Cast insitu	Elastomeric	None	23	9	5	974
217	S	River bridge	Simply supported	Cast insitu	Elastomeric	Thorma Joint	23	9	11	985
218	S	Road bridge	Continuous	Cast insitu	Malthoid (slip membrane)	Asphaltic plug	23	9	2	987
219	W	River bridge	Simply supported	Precast	Elastomeric	Buried under surfacing	23	9	8	995
220	W	Road bridge	Continuous	Cast insitu	Malthoid (slip membrane)	Asphaltic plug	23	9	9	1004
221	E	River bridge	Arch	Cast insitu	None	None	23	9	1	1005
222	E	River bridge	Simply supported	Precast	Pot or Spherical	Elastomeric	23	9	1	1006
223	E	Road bridge	Simply supported	Cast insitu	Elastomeric	Asphaltic plug	23	9	1	1007
224	E	Road bridge	Simply supported	Cast insitu	Pot or Spherical	Asphaltic plug	23	9	1	1008
225	N	Rail bridge	Continuous	Precast	None	Other	23	9	15	1023
226	N	River bridge	Arch	Cast insitu	None	None	23	9	11	1034
227	N	River bridge	Simply supported	Precast	Elastomeric	Elastomeric	23	9	3	1037
228	N	River bridge	Simply supported	Precast	Pot or Spherical	Elastomeric	23	9	3	1040

S/N	Region	Bridge Description	Bridge Type	Deck Construction Method	Bearing Type	Expansion Joint	Rank	Final rank	Number of bridges	Cumulative number of bridges
229	N	Road bridge	Frame	Cast insitu	Other	Thorma Joint	23	9	1	1041
230	N	Road bridge	Simply supported	Cast insitu	Elastomeric	Asphaltic plug	23	9	2	1043
231	S	Road bridge	Simply supported	Cast insitu	Elastomeric	Asphaltic plug	23	9	1	1044
232	W	Road bridge	Simply supported	Cast insitu	Elastomeric	Asphaltic plug	23	9	1	1045
233	E	Pedestrian bridge	Continuous	Cast insitu	None	Asphaltic plug	23	9	1	1046
234	E	Rail bridge	Continuous	Cast insitu	None	None	23	9	1	1047
235	E	River bridge	Continuous	Cast insitu	None	None	23	9	1	1048
236	E	Road bridge	Continuous	Cast insitu	Other	Asphaltic plug	23	9	1	1049
237	E	Road bridge	Frame	Cast insitu	None	None	23	9	4	1053
238	N	River bridge	Continuous	Cast insitu	None	None	23	9	6	1059
239	N	River bridge	Continuous	Cast insitu	None	Thorma Joint	23	9	2	1061
240	N	River bridge	Continuous	Precast	None	Buried under surfacing	23	9	2	1063
241	N	Road bridge	Frame	Cast insitu	None	None	23	9	5	1068
242	N	Road bridge	Frame	Cast insitu	None	Thorma Joint	23	9	1	1069
243	S	Road bridge	Frame	Cast insitu	None	None	23	9	7	1076
244	S	Road bridge	Frame	Cast insitu	None	Thorma Joint	23	9	1	1077
245	W	River bridge	Continuous	Cast insitu	None	None	23	9	4	1081
246	W	River bridge	Continuous	Cast insitu	Rocker Steel or concrete	Thorma Joint	23	9	13	1094
247	E	Road bridge	Continuous	Cast insitu	None	Asphaltic plug	23	9	1	1095
248	N	Rail bridge	Continuous	Precast	Rocker Steel or concrete	Elastomeric	23	9	7	1102
249	N	Road bridge	Continuous	Cast insitu	None	Asphaltic plug	23	9	10	1112
250	S	Road bridge	Continuous	Cast insitu	None	Asphaltic plug	23	9	14	1126
251	N	Road bridge	Simply supported	Precast	Malthoid (slip membrane)	Other	24	10	57	1183
252	S	Road bridge	Simply supported	Precast	Malthoid (slip membrane)	Other	24	10	154	1337
253	E	Road bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	None	24	10	4	1341
254	E	Road bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Thorma Joint	24	10	29	1370
255	E	Road bridge	Simply supported	Precast	Malthoid (slip membrane)	Buried under surfacing	24	10	16	1386
256	N	Road bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	None	24	10	22	1408
257	N	Road bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Thorma Joint	24	10	1	1409
258	N	Road bridge	Simply supported	Precast	Malthoid (slip membrane)	Buried under surfacing	24	10	3	1412
259	S	Road bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	None	24	10	2	1414
260	S	Road bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Thorma Joint	24	10	4	1418
261	W	Road bridge	Simply supported	Cast insitu	Malthoid (slip membrane)	Thorma Joint	24	10	1	1419
262	W	Road bridge	Simply supported	Precast	Malthoid (slip membrane)	Buried under surfacing	24	10	4	1423
263	E	Rail bridge	Continuous	Cast insitu	Pot or Spherical	Other	24	10	3	1426
264	E	River bridge	Continuous	Cast insitu	Elastomeric	Other	24	10	2	1428
265	E	River bridge	Continuous	Cast insitu	Pot or Spherical	Other	24	10	2	1430
266	E	Utility bridge	Simply supported	Cast insitu	Other	Asphaltic plug	24	10	1	1431

S/N	Region	Bridge Description	Bridge Type	Deck Construction Method	Bearing Type	Expansion Joint	Rank	Final rank	Number of bridges	Cumulative number of bridges
267	N	Pedestrian bridge	Simply supported	Precast	Rocker Steel or concrete	Other	24	10	2	1433
268	N	Rail bridge	Simply supported	Steel girder	Other	None	24	10	1	1434
269	N	River bridge	Continuous	Cast insitu	Elastomeric	Other	24	10	1	1435
270	N	River bridge	Continuous	Cast insitu	Pot or Spherical	Other	24	10	4	1439
271	N	Road bridge	Frame	Cast insitu	Elastomeric	Other	24	10	4	1443
272	N	Road bridge	Simply supported	Precast	Malthoid (slip membrane)	Elastomeric	24	10	4	1447
273	N	Road bridge	Simply supported	Precast	Other	Other	24	10	7	1454
274	S	River bridge	Continuous	Cast insitu	Elastomeric	Other	24	10	3	1457
275	S	River bridge	Continuous	Cast insitu	Pot or Spherical	Other	24	10	1	1458
276	W	River bridge	Continuous	Cast insitu	Pot or Spherical	Other	24	10	5	1463
277	E	Rail bridge	Continuous	Cast insitu	Pot or Spherical	Buried under surfacing	24	10	2	1465
278	E	River bridge	Continuous	Cast insitu	Pot or Spherical	Buried under surfacing	24	10	4	1469
279	E	Road bridge	Simply supported	Cast insitu	Other	Thorma Joint	24	10	2	1471
280	E	Road bridge	Simply supported	Precast	Other	Buried under surfacing	24	10	1	1472
281	N	Pedestrian bridge	Simply supported	Cast insitu	None	None	24	10	1	1473
282	N	Pedestrian bridge	Simply supported	Precast	Rocker Steel or concrete	Buried under surfacing	24	10	2	1475
283	N	Rail bridge	Continuous	Cast insitu	Elastomeric	Buried under surfacing	24	10	4	1479
284	N	Rail bridge	Continuous	Cast insitu	Pot or Spherical	Buried under surfacing	24	10	3	1482
285	N	River bridge	Continuous	Cast insitu	Elastomeric	Buried under surfacing	24	10	2	1484
286	N	River bridge	Continuous	Precast	Elastomeric	Asphaltic plug	24	10	2	1486
287	N	River bridge	Continuous	Precast	Pot or Spherical	Asphaltic plug	24	10	1	1487
288	N	Road bridge	Simply supported	Precast	Other	Buried under surfacing	24	10	1	1488
289	S	Road bridge	Simply supported	Cast insitu	Other	Thorma Joint	24	10	1	1489
290	E	River bridge	Continuous	Cast insitu	Elastomeric	Elastomeric	24	10	1	1490
291	E	River bridge	Continuous	Cast insitu	Pot or Spherical	Elastomeric	24	10	1	1491
292	E	Road bridge	Simply supported	Cast insitu	None	None	24	10	1	1492
293	N	Rail bridge	Continuous	Cast insitu	Pot or Spherical	Elastomeric	24	10	5	1497
294	N	River bridge	Continuous	Cast insitu	Elastomeric	Elastomeric	24	10	7	1504
295	N	River bridge	Continuous	Cast insitu	Pot or Spherical	Elastomeric	24	10	7	1511
296	N	Road bridge	Frame	Cast insitu	Elastomeric	Elastomeric	24	10	1	1512
297	N	Road bridge	Frame	Cast insitu	Pot or Spherical	Elastomeric	24	10	13	1525
298	N	Road bridge	Simply supported	Cast insitu	None	None	24	10	5	1530
299	N	Road bridge	Simply supported	Precast	Rocker Steel or concrete	Buried under surfacing	24	10	15	1545
300	S	River bridge	Continuous	Cast insitu	Elastomeric	Elastomeric	24	10	19	1564
301	S	River bridge	Continuous	Cast insitu	Pot or Spherical	Elastomeric	24	10	13	1577
302	S	Road bridge	Simply supported	Precast	None	Buried under surfacing	24	10	1	1578
303	W	Road bridge	Frame	Cast insitu	Pot or Spherical	Elastomeric	24	10	2	1580
304	N	Road bridge	Simply supported	Precast	None	Elastomeric	24	10	1	1581

S/N	Region	Bridge Description	Bridge Type	Deck Construction Method	Bearing Type	Expansion Joint	Rank	Final rank	Number of bridges	Cumulative number of bridges
305	N	River bridge	Cellular	Cast insitu	Malthoid (slip membrane)	Buried under surfacing	25	11	5	1586
306	E	Pedestrian bridge	Simply supported	Cast insitu	Elastomeric	Other	25	11	1	1587
307	E	Road bridge	Continuous	Cast insitu	Malthoid (slip membrane)	Other	25	11	3	1590
308	N	Pedestrian bridge	Simply supported	Cast insitu	Elastomeric	Other	25	11	7	1597
309	N	Rail bridge	Simply supported	Steel girder	Pot or Spherical	Other	25	11	3	1600
310	N	Road bridge	Continuous	Cast insitu	Malthoid (slip membrane)	Other	25	11	1	1601
311	S	Road bridge	Continuous	Cast insitu	Malthoid (slip membrane)	Other	25	11	21	1622
312	E	River bridge	Simply supported	Cast insitu	Pot or Spherical	Sliding steel plates	25	11	7	1629
313	E	River bridge	Simply supported	Precast	Elastomeric	Thorma Joint	25	11	1	1630
314	E	Road bridge	Continuous	Cast insitu	Malthoid (slip membrane)	Buried under surfacing	25	11	3	1633
315	E	Road bridge	Simply supported	Cast insitu	Elastomeric	Other	25	11	1	1634
316	E	Road bridge	Simply supported	Cast insitu	Pot or Spherical	Other	25	11	19	1653
317	N	Pedestrian bridge	Frame	Precast	Other	None	25	11	6	1659
318	N	Pedestrian bridge	Simply supported	Cast insitu	Elastomeric	Buried under surfacing	25	11	55	1714
319	N	River bridge	Cellular	Cast insitu	None	Other	25	11	91	1805
320	N	River bridge	Simply supported	Precast	Elastomeric	Thorma Joint	25	11	17	1822
321	N	Road bridge	Arch	Cast insitu	Malthoid (slip membrane)	Elastomeric	25	11	1	1823
322	N	Road bridge	Continuous	Cast insitu	Malthoid (slip membrane)	Buried under surfacing	25	11	2	1825
323	N	Road bridge	Simply supported	Cast insitu	Elastomeric	Other	25	11	1	1826
324	N	Road bridge	Simply supported	Cast insitu	Pot or Spherical	Other	25	11	3	1829
325	S	River bridge	Simply supported	Precast	Elastomeric	Thorma Joint	25	11	14	1843
326	S	River bridge	Simply supported	Precast	Pot or Spherical	Thorma Joint	25	11	4	1847
327	S	Road bridge	Continuous	Cast insitu	Malthoid (slip membrane)	Buried under surfacing	25	11	1	1848
328	S	Road bridge	Simply supported	Cast insitu	Elastomeric	Other	25	11	2	1850
329	W	River bridge	Simply supported	Precast	Elastomeric	Thorma Joint	25	11	1	1851
330	W	Road bridge	Simply supported	Cast insitu	Elastomeric	Other	25	11	4	1855
331	E	River bridge	Cellular	Cast insitu	None	Buried under surfacing	25	11	10	1865
332	E	River bridge	Continuous	Precast	Other	None	25	11	7	1872
333	E	Road bridge	Continuous	Cast insitu	Malthoid (slip membrane)	Elastomeric	25	11	1	1873
334	E	Road bridge	Continuous	Cast insitu	Other	Other	25	11	1	1874
335	E	Road bridge	Simply supported	Cast insitu	Elastomeric	Buried under surfacing	25	11	1	1875
336	E	Road bridge	Simply supported	Precast	Elastomeric	Asphaltic plug	25	11	1	1876
337	N	Pedestrian bridge	Continuous	Cast insitu	None	Other	25	11	3	1879
338	N	Pedestrian bridge	Frame	Steel girder	Other	Elastomeric	25	11	1	1880
339	N	River bridge	Arch	Precast	None	None	25	11	1	1881
340	N	River bridge	Cellular	Cast insitu	None	Buried under surfacing	25	11	3	1884
341	N	River bridge	Continuous	Cast insitu	Roller	Buried under surfacing	25	11	16	1900
342	N	Road bridge	Continuous	Cast insitu	Malthoid (slip membrane)	Elastomeric	25	11	13	1913

S/N	Region	Bridge Description	Bridge Type	Deck Construction Method	Bearing Type	Expansion Joint	Rank	Final rank	Number of bridges	Cumulative number of bridges
343	N	Road bridge	Continuous	Cast insitu	Other	Other	25	11	8	1921
344	N	Road bridge	Simply supported	Cast insitu	Elastomeric	Buried under surfacing	25	11	2	1923
345	N	Road bridge	Simply supported	Precast	Elastomeric	Asphaltic plug	25	11	1	1924
346	S	Road bridge	Simply supported	Precast	Elastomeric	Asphaltic plug	25	11	1	1925
347	S	Road bridge	Simply supported	Precast	Pot or Spherical	Asphaltic plug	25	11	5	1930
348	W	River bridge	Arch	Precast	None	None	25	11	1	1931
349	W	River bridge	Cellular	Cast insitu	None	Buried under surfacing	25	11	7	1938
350	W	Road bridge	Simply supported	Precast	Elastomeric	Asphaltic plug	25	11	5	1943
351	E	Road bridge	Continuous	Cast insitu	None	Other	25	11	15	1958
352	E	Road bridge	Continuous	Cast insitu	Rocker Steel or concrete	Other	25	11	1	1959
353	E	Road bridge	Simply supported	Cast insitu	Elastomeric	Elastomeric	25	11	18	1977
354	E	Road bridge	Simply supported	Cast insitu	Pot or Spherical	Elastomeric	25	11	25	2002
355	N	Road bridge	Continuous	Cast insitu	None	Other	25	11	16	2018
356	N	Road bridge	Continuous	Cast insitu	Other	Buried under surfacing	25	11	32	2050
357	N	Road bridge	Continuous	Cast insitu	Rocker Steel or concrete	Other	25	11	4	2054
358	N	Road bridge	Frame	Precast	None	None	25	11	9	2063
359	N	Road bridge	Simply supported	Cast insitu	Elastomeric	Elastomeric	25	11	7	2070
360	N	Road bridge	Simply supported	Cast insitu	Pot or Spherical	Elastomeric	25	11	10	2080
361	S	Road bridge	Continuous	Cast insitu	None	Other	25	11	2	2082
362	S	Road bridge	Simply supported	Cast insitu	Elastomeric	Elastomeric	25	11	4	2086
363	W	Road bridge	Continuous	Cast insitu	None	Other	25	11	1	2087
364	E	Road bridge	Continuous	Cast insitu	None	Buried under surfacing	25	11	1	2088
365	E	Road bridge	Continuous	Cast insitu	Other	Elastomeric	25	11	11	2099
366	N	Road bridge	Continuous	Cast insitu	None	Buried under surfacing	25	11	3	2102
367	S	Road bridge	Continuous	Cast insitu	Other	Elastomeric	25	11	10	2112
368	W	Road bridge	Continuous	Cast insitu	None	Buried under surfacing	25	11	5	2117
369	E	Road bridge	Continuous	Cast insitu	None	Elastomeric	25	11	5	2122
370	N	Road bridge	Continuous	Cast insitu	None	Elastomeric	25	11	4	2126
371	S	Road bridge	Continuous	Cast insitu	None	Elastomeric	25	11	9	2135
372	W	Road bridge	Continuous	Cast insitu	None	Elastomeric	25	11	1	2136
373	N	Canal bridge (under	Simply supported	Cast insitu	Malthoid (slip membrane)	Buried under surfacing	26	12	21	2157
374	E	Road bridge	Simply supported	Precast	Malthoid (slip membrane)	None	26	12	14	2171
375	E	Road bridge	Simply supported	Steel girder	Malthoid (slip membrane)	Buried under surfacing	26	12	4	2175
376	N	Pedestrian bridge	Frame	Precast	Elastomeric	Other	26	12	7	2182
377	N	Road bridge	Simply supported	Precast	Malthoid (slip membrane)	None	26	12	1	2183
378	N	Road bridge	Simply supported	Precast	Malthoid (slip membrane)	Thorma Joint	26	12	3	2186
379	W	Road bridge	Simply supported	Precast	Malthoid (slip membrane)	Thorma Joint	26	12	3	2189
380	E	River bridge	Continuous	Precast	Elastomeric	Other	26	12	2	2191

S/N	Region	Bridge Description	Bridge Type	Deck Construction Method	Bearing Type	Expansion Joint	Rank	Final rank	Number of bridges	Cumulative number of bridges
381	N	River bridge	Continuous	Precast	Elastomeric	Other	26	12	1	2192
382	S	River bridge	Continuous	Precast	Pot or Spherical	Other	26	12	1	2193
383	E	River bridge	Continuous	Cast insitu	Elastomeric	None	26	12	1	2194
384	E	River bridge	Continuous	Cast insitu	Pot or Spherical	Thorma Joint	26	12	1	2195
385	N	Rail bridge	Continuous	Cast insitu	Elastomeric	None	26	12	1	2196
386	N	Rail bridge	Continuous	Cast insitu	Elastomeric	Thorma Joint	26	12	1	2197
387	N	River bridge	Continuous	Cast insitu	Elastomeric	None	26	12	4	2201
388	N	River bridge	Continuous	Cast insitu	Elastomeric	Thorma Joint	26	12	1	2202
389	N	River bridge	Continuous	Cast insitu	Pot or Spherical	Thorma Joint	26	12	1	2203
390	S	River bridge	Continuous	Cast insitu	Elastomeric	Thorma Joint	26	12	2	2205
391	E	Road bridge	Continuous	Cast insitu	Elastomeric	Asphaltic plug	26	12	1	2206
392	E	Road bridge	Continuous	Cast insitu	Pot or Spherical	Asphaltic plug	26	12	1	2207
393	N	River bridge	Continuous	Precast	Elastomeric	Elastomeric	26	12	1	2208
394	N	River bridge	Continuous	Precast	Pot or Spherical	Elastomeric	26	12	1	2209
395	N	Road bridge	Continuous	Cast insitu	Elastomeric	Asphaltic plug	26	12	1	2210
396	N	Road bridge	Continuous	Cast insitu	Pot or Spherical	Asphaltic plug	26	12	2	2212
397	S	River bridge	Continuous	Precast	Elastomeric	Elastomeric	26	12	4	2216
398	S	River bridge	Continuous	Precast	Pot or Spherical	Elastomeric	26	12	1	2217
399	S	Road bridge	Continuous	Cast insitu	Elastomeric	Asphaltic plug	26	12	1	2218
400	S	Road bridge	Continuous	Cast insitu	Pot or Spherical	Asphaltic plug	26	12	2	2220
401	W	River bridge	Continuous	Precast	Pot or Spherical	Elastomeric	26	12	2	2222
402	W	Road bridge	Continuous	Cast insitu	Elastomeric	Asphaltic plug	26	12	1	2223
403	W	Road bridge	Continuous	Cast insitu	Pot or Spherical	Asphaltic plug	26	12	1	2224
404	N	River bridge	Cellular	Cast insitu	Malthoid (slip membrane)	None	27	13	5	2229
405	E	Road bridge	Cellular	Cast insitu	Malthoid (slip membrane)	Asphaltic plug	27	13	3	2232
406	N	Pedestrian bridge	Simply supported	Precast	Pot or Spherical	Other	27	13	1	2233
407	E	Road bridge	Continuous	Cast insitu	Malthoid (slip membrane)	Thorma Joint	27	13	2	2235
408	E	Road bridge	Simply supported	Precast	Elastomeric	Other	27	13	4	2239
409	N	River bridge	Simply supported	Steel girder	Pot or Spherical	Thorma Joint	27	13	2	2241
410	N	Road bridge	Continuous	Cast insitu	Malthoid (slip membrane)	Thorma Joint	27	13	3	2244
411	N	Road bridge	Continuous	Precast	Malthoid (slip membrane)	Buried under surfacing	27	13	1	2245
412	N	Road bridge	Simply supported	Precast	Elastomeric	Other	27	13	1	2246
413	N	Road bridge	Simply supported	Precast	Pot or Spherical	Other	27	13	2	2248
414	S	Road bridge	Continuous	Cast insitu	Malthoid (slip membrane)	Thorma Joint	27	13	3	2251
415	S	Road bridge	Simply supported	Precast	Elastomeric	Other	27	13	2	2253
416	S	Road bridge	Simply supported	Precast	Pot or Spherical	Other	27	13	2	2255
417	E	River bridge	Arch	Steel girder	None	None	27	13	5	2260
418	E	River bridge	Cellular	Cast insitu	None	None	27	13	4	2264

S/N	Region	Bridge Description	Bridge Type	Deck Construction Method	Bearing Type	Expansion Joint	Rank	Final rank	Number of bridges	Cumulative number of bridges
419	E	Road bridge	Simply supported	Cast insitu	Elastomeric	None	27	13	6	2270
420	E	Road bridge	Simply supported	Cast insitu	Elastomeric	Thorma Joint	27	13	2	2272
421	E	Road bridge	Simply supported	Cast insitu	Pot or Spherical	Thorma Joint	27	13	5	2277
422	E	Road bridge	Simply supported	Precast	Elastomeric	Buried under surfacing	27	13	3	2280
423	N	River bridge	Cellular	Cast insitu	None	None	27	13	9	2289
424	N	Road bridge	Simply supported	Cast insitu	Elastomeric	None	27	13	6	2295
425	N	Road bridge	Simply supported	Cast insitu	Elastomeric	Thorma Joint	27	13	3	2298
426	N	Road bridge	Simply supported	Cast insitu	Pot or Spherical	None	27	13	1	2299
427	N	Road bridge	Simply supported	Cast insitu	Pot or Spherical	Thorma Joint	27	13	4	2303
428	N	Road bridge	Simply supported	Precast	Elastomeric	Buried under surfacing	27	13	1	2304
429	N	Road bridge	Simply supported	Precast	Pot or Spherical	Buried under surfacing	27	13	1	2305
430	S	River bridge	Cellular	Cast insitu	None	None	27	13	1	2306
431	S	Road bridge	Simply supported	Cast insitu	Elastomeric	Thorma Joint	27	13	1	2307
432	W	Road bridge	Simply supported	Cast insitu	Elastomeric	Thorma Joint	27	13	2	2309
433	W	Road bridge	Simply supported	Precast	Elastomeric	Buried under surfacing	27	13	1	2310
434	E	Road bridge	Arch	Cast insitu	None	None	27	13	3	2313
435	N	Pedestrian bridge	Continuous	Cast insitu	Rocker Steel or concrete	None	27	13	3	2316
436	N	River bridge	Cellular	Precast	None	Elastomeric	27	13	1	2317
437	N	Road bridge	Continuous	Cast insitu	Other	Thorma Joint	27	13	1	2318
438	N	Road bridge	Continuous	Precast	None	Other	27	13	1	2319
439	N	Road bridge	Simply supported	Precast	Elastomeric	Elastomeric	27	13	4	2323
440	N	Road bridge	Simply supported	Precast	Pot or Spherical	Elastomeric	27	13	2	2325
441	S	Road bridge	Simply supported	Precast	Elastomeric	Elastomeric	27	13	7	2332
442	S	Road bridge	Simply supported	Precast	Pot or Spherical	Elastomeric	27	13	2	2334
443	W	Road bridge	Continuous	Cast insitu	Other	None	27	13	4	2338
444	E	Road bridge	Continuous	Cast insitu	None	None	27	13	1	2339
445	N	Road bridge	Continuous	Cast insitu	None	None	27	13	1	2340
446	N	Road bridge	Continuous	Cast insitu	None	Thorma Joint	27	13	1	2341
447	S	Road bridge	Continuous	Cast insitu	None	None	27	13	1	2342
448	N	Canal bridge (under	Simply supported	Cast insitu	Malthoid (slip membrane)	None	28	14	2	2344
449	N	Viaduct (valley brid	Simply supported	Cast insitu	Malthoid (slip membrane)	None	28	14	1	2345
450	E	Pedestrian bridge	Continuous	Cast insitu	Elastomeric	Other	28	14	4	2349
451	N	Pedestrian bridge	Continuous	Cast insitu	Pot or Spherical	Other	28	14	2	2351
452	N	Pedestrian bridge	Simply supported	Steel girder	Other	None	28	14	1	2352
453	N	River bridge	Continuous	Balanced cantilever	Pot or Spherical	Other	28	14	5	2357
454	N	River bridge	Continuous	Steel girder	Pot or Spherical	Other	28	14	2	2359
455	W	Pedestrian bridge	Continuous	Cast insitu	Pot or Spherical	Other	28	14	9	2368
456	E	Road bridge	Continuous	Cast insitu	Elastomeric	Other	28	14	30	2398

S/N	Region	Bridge Description	Bridge Type	Deck Construction Method	Bearing Type	Expansion Joint	Rank	Final rank	Number of bridges	Cumulative number of bridges
457	N	River bridge	Continuous	Precast	Elastomeric	Thorma Joint	28	14	15	2413
458	N	Road bridge	Continuous	Cast insitu	Elastomeric	Other	28	14	4	2417
459	N	Road bridge	Continuous	Cast insitu	Pot or Spherical	Other	28	14	1	2418
460	S	River bridge	Continuous	Precast	Elastomeric	Thorma Joint	28	14	1	2419
461	S	River bridge	Continuous	Precast	Pot or Spherical	Thorma Joint	28	14	1	2420
462	S	Road bridge	Continuous	Cast insitu	Elastomeric	Other	28	14	1	2421
463	S	Road bridge	Continuous	Cast insitu	Pot or Spherical	Other	28	14	3	2424
464	W	Road bridge	Continuous	Cast insitu	Elastomeric	Other	28	14	4	2428
465	W	Road bridge	Continuous	Cast insitu	Pot or Spherical	Other	28	14	2	2430
466	E	Road bridge	Continuous	Cast insitu	Elastomeric	Buried under surfacing	28	14	3	2433
467	E	Road bridge	Continuous	Cast insitu	Pot or Spherical	Buried under surfacing	28	14	2	2435
468	E	Road bridge	Continuous	Precast	Pot or Spherical	Asphaltic plug	28	14	4	2439
469	N	Pedestrian bridge	Continuous	Cast insitu	Pot or Spherical	Elastomeric	28	14	6	2445
470	N	Road bridge	Arch	Cast insitu	Elastomeric	Elastomeric	28	14	2	2447
471	N	Road bridge	Continuous	Cast insitu	Elastomeric	Buried under surfacing	28	14	2	2449
472	N	Road bridge	Continuous	Cast insitu	Pot or Spherical	Buried under surfacing	28	14	1	2450
473	N	Road bridge	Continuous	Precast	Elastomeric	Asphaltic plug	28	14	4	2454
474	N	Road bridge	Continuous	Precast	Pot or Spherical	Asphaltic plug	28	14	2	2456
475	S	Road bridge	Continuous	Cast insitu	Elastomeric	Buried under surfacing	28	14	1	2457
476	S	Road bridge	Continuous	Cast insitu	Pot or Spherical	Buried under surfacing	28	14	1	2458
477	W	Road bridge	Continuous	Cast insitu	Pot or Spherical	Buried under surfacing	28	14	2	2460
478	E	Road bridge	Continuous	Cast insitu	Elastomeric	Elastomeric	28	14	1	2461
479	E	Road bridge	Continuous	Cast insitu	Pot or Spherical	Elastomeric	28	14	2	2463
480	N	Road bridge	Continuous	Cast insitu	Elastomeric	Elastomeric	28	14	4	2467
481	N	Road bridge	Continuous	Cast insitu	Pot or Spherical	Elastomeric	28	14	9	2476
482	S	Road bridge	Continuous	Cast insitu	Elastomeric	Elastomeric	28	14	3	2479
483	S	Road bridge	Continuous	Cast insitu	Pot or Spherical	Elastomeric	28	14	3	2482
484	W	Road bridge	Continuous	Cast insitu	Elastomeric	Elastomeric	28	14	1	2483
485	W	Road bridge	Continuous	Cast insitu	Pot or Spherical	Elastomeric	28	14	1	2484
486	E	Canal bridge (under	Simply supported	Cast insitu	Elastomeric	Other	29	15	1	2485
487	E	Road bridge	Cellular	Cast insitu	Malthoid (slip membrane)	Buried under surfacing	29	15	4	2489
488	E	Utility bridge	Simply supported	Cast insitu	Elastomeric	Buried under surfacing	29	15	1	2490
489	N	Road bridge	Continuous	Precast	Malthoid (slip membrane)	None	29	15	1	2491
490	N	Utility bridge	Frame	Precast	Other	None	29	15	2	2493
491	E	River bridge	Cellular	Balanced cantilever	None	Buried under surfacing	29	15	1	2494
492	E	Road bridge	Simply supported	Precast	Elastomeric	Thorma Joint	29	15	1	2495
493	N	Rail bridge	Arch	Steel girder	Concrete Hinge and Pad	Elastomeric	29	15	1	2496
494	N	River bridge	Cellular	Precast	None	None	29	15	2	2498

S/N	Region	Bridge Description	Bridge Type	Deck Construction Method	Bearing Type	Expansion Joint	Rank	Final rank	Number of bridges	Cumulative number of bridges
495	N	Road bridge	Simply supported	Precast	Elastomeric	None	29	15	4	2502
496	N	Road bridge	Simply supported	Precast	Elastomeric	Thorma Joint	29	15	2	2504
497	N	Road bridge	Simply supported	Precast	Pot or Spherical	Thorma Joint	29	15	2	2506
498	S	Road bridge	Simply supported	Precast	Elastomeric	Thorma Joint	29	15	2	2508
499	W	Road bridge	Simply supported	Precast	Elastomeric	Thorma Joint	29	15	3	2511
500	N	River bridge	Lattice truss girders	Steel girder	Rocker Steel or concrete	Elastomeric	29	15	1	2512
501	N	Road bridge	Cellular	Cast insitu	None	Buried under surfacing	29	15	2	2514
502	S	Road bridge	Cellular	Cast insitu	None	Buried under surfacing	29	15	1	2515
503	N	Road bridge	Continuous	Cast insitu	Concrete Hinge and Pad	Elastomeric	29	15	2	2517
504	E	Pedestrian bridge	Continuous	Cast insitu	Elastomeric	None	30	16	1	2518
505	N	Road bridge	Arch	Cast insitu	Elastomeric	Thorma Joint	30	16	3	2521
506	N	Road bridge	Cantilever	Cast insitu	Pot or Spherical	Asphaltic plug	30	16	2	2523
507	N	Road bridge	Continuous	Precast	Elastomeric	Other	30	16	1	2524
508	N	Road bridge	Continuous	Precast	Pot or Spherical	Other	30	16	3	2527
509	S	Road bridge	Cantilever	Cast insitu	Elastomeric	Asphaltic plug	30	16	3	2530
510	S	Road bridge	Continuous	Precast	Pot or Spherical	Other	30	16	2	2532
511	E	Road bridge	Continuous	Cast insitu	Elastomeric	Thorma Joint	30	16	3	2535
512	N	Road bridge	Continuous	Cast insitu	Elastomeric	Thorma Joint	30	16	1	2536
513	N	Road bridge	Continuous	Cast insitu	Pot or Spherical	Thorma Joint	30	16	1	2537
514	S	Road bridge	Continuous	Cast insitu	Elastomeric	Thorma Joint	30	16	1	2538
515	E	Road bridge	Continuous	Precast	Pot or Spherical	Elastomeric	30	16	1	2539
516	N	Road bridge	Continuous	Precast	Elastomeric	Elastomeric	30	16	2	2541
517	N	Road bridge	Continuous	Precast	Pot or Spherical	Elastomeric	30	16	3	2544
518	S	Road bridge	Continuous	Precast	Pot or Spherical	Elastomeric	30	16	1	2545
519	N	Canal bridge (under	Simply supported	Precast	Elastomeric	Other	31	17	3	2548
520	N	Utility bridge	Simply supported	Precast	Pot or Spherical	Other	31	17	3	2551
521	N	Viaduct (valley brid	Simply supported	Precast	Elastomeric	Other	31	17	3	2554
522	E	Road bridge	Cellular	Cast insitu	None	None	31	17	3	2557
523	N	Road bridge	Cellular	Cast insitu	None	None	31	17	1	2558
524	N	Road bridge	Continuous	Precast	Concrete Hinge and Pad	Elastomeric	31	17	1	2559
525	E	Road bridge	Cable stayed	Cast insitu	Pot or Spherical	Other	32	18	3	2562
526	E	Pedestrian bridge	Continuous	Cast insitu	Elastomeric	Sliding steel plates	32	18	5	2567
527	N	Pedestrian bridge	Cable stayed	Cast insitu	Pot or Spherical	Elastomeric	32	18	2	2569
528	N	Road bridge	Continuous	Steel girder	Pot or Spherical	Other	32	18	1	2570
529	E	Canal bridge (under	Continuous	Cast insitu	Elastomeric	Elastomeric	32	18	2	2572
530	N	Road bridge	Continuous	Precast	Elastomeric	Thorma Joint	32	18	1	2573
531	N	Road bridge	Continuous	Precast	Pot or Spherical	Thorma Joint	32	18	10	2583
532	S	Road bridge	Continuous	Precast	Elastomeric	Thorma Joint	32	18	8	2591

S/N	Region	Bridge Description	Bridge Type	Deck Construction Method	Bearing Type	Expansion Joint	Rank	Final rank	Number of bridges	Cumulative number of bridges
533	N	Road bridge	Continuous	Steel girder	Pot or Spherical	Elastomeric	32	18	5	2596
534	N	Canal bridge (under	Arch	Precast	Concrete Hinge and Pad	Asphaltic plug	33	19	1	2597
535	N	Canal bridge (under	Simply supported	Precast	Elastomeric	Thorma Joint	33	19	1	2598
536	N	Pedestrian bridge	Cellular	Precast	Other	None	33	19	1	2599
537	E	Canal bridge (under	Cellular	Cast insitu	None	Buried under surfacing	33	19	7	2606
538	N	Canal bridge (under	Cellular	Cast insitu	None	Buried under surfacing	33	19	7	2613
539	S	Canal bridge (under	Cellular	Cast insitu	None	Buried under surfacing	33	19	2	2615
540	N	Pedestrian bridge	Cable stayed	Precast	Elastomeric	Other	34	20	2	2617
541	N	Pedestrian bridge	Lattice truss girders	Precast	Pot or Spherical	Other	34	20	2	2619
542	E	Utility bridge	Continuous	Precast	Elastomeric	Other	34	20	1	2620
543	N	Road bridge	Articulated structure	Precast	Elastomeric	Other	34	20	1	2621
544	N	Pedestrian bridge	Cable stayed	Precast	Pot or Spherical	Elastomeric	34	20	2	2623
545	S	Road bridge	Cantilever	Cast insitu	Elastomeric	Thorma Joint	34	20	1	2624
546	S	Utility bridge	Continuous	Cast insitu	Elastomeric	Thorma Joint	34	20	5	2629
547	N	Viaduct (valley brid	Continuous	Precast	Pot or Spherical	Elastomeric	34	20	1	2630
548	S	Viaduct (valley brid	Continuous	Precast	Pot or Spherical	Elastomeric	34	20	1	2631
549	E	Viaduct (valley brid	Simply supported	Balanced cantilever	Elastomeric	None	35	21	1	2632
550	N	Road bridge	Cable stayed	Precast	Concrete Hinge and Pad	Buried under surfacing	35	21	1	2633
551	N	Road bridge	Cantilever	Balanced cantilever	Pot or Spherical	Other	36	22	1	2634
552	N	Canal bridge (under	Cellular	Precast	None	None	37	23	1	2635