DEVELOPING A PAVEMENT CONDITION ASSESSMENT METHOD FOR UNPAVED ROADS IN UGANDA

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ABSTRACT

Approximately 95% of Uganda's total road network consists of unpaved surfaces, a situation that is prevalent across most developing countries in the world. This heavy reliance on unpaved roads poses significant challenges, as these roads are highly susceptible to rapid deterioration due to the combined effects of traffic and environmental factors. Consistent monitoring and evaluation of the condition of these unpaved roads is, therefore, crucial to ensure the safety and reliability of the transportation infrastructure. However, the current methods employed for assessing the condition of unpaved roads are often subjective, labor-intensive, and time-consuming, frequently leading to inconsistent evaluations.

This PhD study proposes an enhanced method for assessing the condition of unpaved roads in Uganda. The methodology used in this study consisted of five stages: research formulation, investigation, model development, model validation and recommendations. A questionnaire survey was conducted during the investigation stage, with a 51.4% response rate from road maintenance professionals spread across the country's six regions. The novel Gravel Road Condition Index (GRCI) utilized the Analytic Hierarchy Process (AHP) to convert the subjective questionnaire survey results into objective mathematical data. The AHP method provided a rigorous and quantitative approach for systematically weighting and ranking the nine key distresses affecting the surface conditions of unpaved roads in the country.

The developed Gravel Road Condition Index was validated by applying the method on a case-study gravel road and verifying the results through comparison with the pre-existing condition assessment method in Uganda. The results demonstrated that the GRCI offered a rapid, efficient, and user-friendly procedure for assessing the condition of unpaved roads, underpinned by objective weightings that demonstrated consistency in its evaluations. This PhD study further established a relationship between the novel GRCI and the current gravel loss prediction model for unpaved roads in Uganda. This relationship can be used to improve maintenance planning and efficiently optimize the already scarce funding resources in the country.

Keywords: *Unpaved roads, road surface distresses, road maintenance, pavement condition assessment, Analytic Hierarchy Process, performance prediction models*

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DEDICATION

*"To my late father **Mr. Dezi Nuwagaba** and my courageous mother **Mrs. Regina Nuwagaba.**"*

AND

*"To my lovely wife **Pamela Nansubuga Musiime** and our two adorable children **Valerie Musiime** and **Ethan Musiime.**"*

DECLARATION

I, Richard Musiime hereby declare that this thesis, titled, ***“Developing A Pavement Condition Assessment Method For Unpaved Roads In Uganda”*** is my work and that no portion of the work covered in this thesis has been submitted to any other academic institution for consideration of any academic qualification award.

Richard Musiime

ABBREVIATIONS

ADRICS	Annual District Inventory and Condition Survey
ADT	Average Daily Traffic
AGL	Annual Gravel Loss
AHP	Analytic Hierarchy Process
ANN	Artificial Neural Network
CVI	Coarse Visual Inspection
DA	Designated Agency
DUCAR	District, Urban, Community and Access Roads
DVI	Detailed Visual Inspection
GDP	Gross Domestic Product
GRCI	Gravel Road Condition Index
IRI	International Roughness Index
MMP	Mean Monthly Precipitation
MoWT	Ministry of Works and Transport
M&R	Maintenance and Rehabilitation
PASER	Pavement Surface Evaluation Rating
PCI	Pavement Condition Index
PMS	Pavement Management Systems
URCI	Unsurfaced Road Condition Index
URF	Uganda Road Fund
UNRA	Uganda National Roads Authority
VCI	Visual Condition Index

DEFINITIONS

Pavement:	The upper layers of the road comprising the selected subgrade, subbase, base, shoulders, and surfacing.
Pavement management:	The process of planning the maintenance and repair of a road network.
Paved road:	A road with a bituminous surface, surface dressing or asphalt surface, or with a concrete or concrete block surface.
Unpaved road:	A road with a gravel or earth surface.
Flexible pavement:	A pavement with a bituminous asphalt or bituminous seal surfacing.
Rigid pavement:	A pavement with a concrete surfacing.

Chapter One

INTRODUCTION

1.1 Background

Roads are an essential national asset. Roads in Europe, for example, account for 83% of the surface passenger transport while rail is only 17% (PIARC, 2014). Developing countries rely more heavily on roads, with more than 95% of goods and passenger traffic making use of this transportation infrastructure. This excessive use makes roads one of the largest and most important national asset that is often publicly owned (PIARC, 2014).

The World Road Association (2014) reaffirms that well maintained roads provide a foundation to economic growth, by accommodating both goods and passenger traffic, despite the continuous growth in traffic volume pressures on this transportation infrastructure. Well maintained roads stimulate the national Gross Domestic Product (GDP), improve social welfare and are a means of safe travel across borders. The commercial transport services benefit of roads is between 3% to 5% of the GDP in developed countries and as such are a major contributor to the economy (Peraka and Biligiri, 2020; PIARC, 2014). It is therefore imperative that this high value asset is well maintained so as to benefit road users and the economy at large.

Adlinge and Gupta (2009) contend that roads undergo constant deterioration during their lifecycle due to several factors such as inadequate maintenance, moisture penetration into the subgrade layers, traffic loading, inadequate quality control during the construction stages and environmental conditions. The World Bank (1988) asserts that leaving deterioration unchecked can lead to huge investment losses because the funds required to restore deteriorated roads is five times greater than would have been if timely and effective maintenance is practiced. Thus, road deterioration can be mitigated through practicing effective pavement management.

Pavement management in its broad sense is a process of planning the maintenance and repair of a road network or other paved facilities such as airport runways and parking lots (AASHTO, 2012; Alfar, 2016). Pavement management applies a scientific approach to effectively managing the maintenance of the road network and is practiced at either a project level (site-specific technical aspects), or a network level (policy and programming), by making use of Pavement Management Systems (Haas, Hudson and Zaniewski, 1994; Obunguta and Matsushima, 2020).

Research into Pavement Management Systems (PMS) started in the late 1960’s and early 1970’s in North America (Canada and USA) due to local authorities being faced with a large amount of maintenance work at the same time following a massive expansion of the road network (Wang et al.,2020; Haas, Hudson and Falls, 2015; Kulkarni and Miller, 2003). Haas and Hudson (1978) pioneered the use of a systems methodology in the pavement management context and published a PMS textbook that laid the foundation to PMS that is still prevalent today. It should be noted that the early PMS evaluated, ranked and prioritized the maintenance and rehabilitation (M&R) needs of roads basing on the surface condition without considering the future maintenance needs or the optimization of limited funding (Alfar, 2016). The current PMS includes pavement condition information, a road network database, performance models, a decision aid tool, quality evaluation tool, and analytical models that predict future maintenance cost needs (Zagvozda et al., 2019).

The condition information of the pavement, both current and historic, are key inputs into the PMS. This information is obtained through scheduled pavement condition assessments and can be used to optimize the maintenance and rehabilitation intervention while also establishing accurate future road condition predications that are sensitive to the limited funding available to most road agencies (Oladele, 2013). Pavement condition assessments include data collection, condition rating and data quality management. These activities are performed to inform agencies of the serviceability and physical condition of the road network (Attoh-Okine and Adarkwa, 2013).

While research into pavement condition assessment methods for paved roads is vast, there is limited available information regarding unpaved roads. This may be because the condition of an unpaved road can change literally overnight and as such researchers have found it difficult to carry out significant studies that can improve the available pavement condition assessment methods for unpaved roads (Cudworth and Rahman (2023); Alzubaidi, 1999; CSIR ,2000; Walker, 2002; USACE, 1995; Brooks et al., 2011). This research is therefore intended to fill the existing information gap regarding pavement condition assessment methods for unpaved roads. This research focuses on developing the Gravel Road Condition Index (GRCI), which aims to provide an improved pavement condition assessment method for unpaved roads in Uganda.

1.2 Problem Statement

The majority of unpaved roads in Uganda are poorly maintained due to the lack of effective pavement condition assessment methods and insufficient funding for maintenance and rehabilitation (M&R) activities. This is a significant issue, as 152,246 km (95%) out of the total 159,461 km road network in Uganda is unpaved, as shown in Table 1.1 (NPA, 2020). Moreover, unpaved roads in Uganda pose an increased risk of accidents and potential vehicle damage due to the loose surface materials and uneven riding surfaces, which can lead to impacts and abrasion, causing damage to tires, wheels, and suspension components (NPA, 2020; MoWT, 2021). The unpredictable nature of the unpaved road surfaces, characterized by loose gravel and uneven crossfall, can result in a loss of traction and control, particularly at higher speeds. This heightened risk is further exacerbated by the difficulty in predicting the behaviour of unpaved roads, which often undergo substantial changes due to weather, usage, and maintenance practices. Consistent monitoring and evaluation of the condition of these unpaved roads is crucial given the high risk of accidents and sudden pavement deterioration caused by traffic and environmental factors.

Unpaved roads in Uganda typically have a 6-meter carriageway width, a 4% to 6% crossfall, and are built using gravel with a maximum aggregate size of 40 mm (MoWT, 2021). The gradient of the carriageway (crossfall) influences the effectiveness of surface and rainwater drainage on unpaved roads. Additionally, the material properties are crucial determinants of the strength and durability of the gravel wearing course, as well as the capacity of the surface aggregate material to resist the crushing forces exerted by traffic (MoWT, 2021). Uganda's road network is categorized into 21,105 km of National Roads *(of which 72% is unpaved)* and 138,356 km of DUCAR roads (District, Urban, Community and Access Roads) *(of which 99% is unpaved)* (NPA,2020). National Roads are managed by the Uganda National Roads Authority (UNRA) while DUCAR are managed by Designated Agencies (DA’s) such as District

Local Governments, Urban and Municipal Councils (MoWT, 2021). The UNRA unpaved road network is maintained through its twenty-three (23) maintenance stations spread across the Central, Eastern, Northern, South-western, Western and North-eastern regions of Uganda using force-account and works contractors (UNRA, 2022).

Road classification	**Length (km)**			**Percentage**	
	Paved	**Unpaved**	**Total**	**Paved**	**Unpaved**
National Roads	5,879	15,227	21,105	28%	72%
DUCAR	1,337	137,019	138,356	1%	99%
Total	**7,216**	**152,246**	**159,461**	**5%**	**95%**

Table 1.1: Summary of Ugandan paved and unpaved road network

Road maintenance engineers employed at the stations are tasked with carrying out manual pavement condition assessments of the unpaved network within their jurisdiction following the UNRA visual condition assessments manual. This manual identifies nine (09) distresses: i.e., Gravel Thickness, Roughness, Potholes, Rutting, Corrugations, Erosion Gullies, Drainage Condition, Drainage Formation Level and Material Quality that are assessed according to a 5-point severity scale (UNRA, 2017). The Visual Condition Index (VCI) that rates the road condition on a 5-point scale of Very Good (100) to Very Poor (0) is used by UNRA to report on the condition of the unpaved National Road network. This UNRA VCI rating is calculated for every 1 km section of unpaved road from the combination of the weighting factor of each distress and the severity of the individual distress (UNRA, 2017). It should be noted that while the UNRA VCI establishes a road condition rating, it does not provide for maintenance and rehabilitation interventions, predict future road condition, or provide a costing estimate for the M&R needs.

On the other hand, the DUCAR unpaved road network is managed and maintained by 121 District Local Governments, 41 Municipal Councils, 1,155 sub-counties and 214 town councils as sub-agencies of the respective District Local Governments (URF, 2022). The District, Municipal and Town Council engineers in these agencies are tasked to carry out visual condition assessments on their respective unpaved road networks following the MoWT Road Maintenance Management Manual (MoWT, 2010c). This manual identifies five (05) distresses i.e., Roughness, Rutting, Loss of Camber, Potholes and Edge step that are assessed using a 4-point grading for severity and a 5-point grading for the extent to determine the condition rating on a scale of 5 (Excellent) to 1 (Very Poor). The MoWT manual is, however, not widely used by the majority of DUCAR agencies because of its complexity, lack of training of the engineers in condition assessment methods and inadequate facilitation of condition assessors. Thus, the lack of an efficient, reliable and simplified condition assessment method for DUCAR agencies has further complicated the limited funds available for road maintenance and rehabilitation activities.

Inadequate funding for road maintenance is also a major challenge for the Ugandan unpaved road network. Established in 2008, the Uganda Road Fund (URF) is the government organisation responsible for funding the country's road maintenance activities (URF, 2022). Prior to its establishment, the government disbursed road maintenance funds directly to the agencies from the treasury. This form of funding was inefficient and led to an accumulation of the maintenance backlog with the road condition for DUCAR rated as poor to very poor condition increasing from 30% to 55% between 1998 to 2008 (MoWT, 2021). URF was therefore established to address the inadequate funding levels of road maintenance by providing an institutional mechanism through which revenues from road user charges could be put at the disposal of agencies without being subjected to the bureaucratic procedures associated with the consolidated government fund (MoWT, 2021). URF has however failed to achieve this because of the legal impediments that prevent URF from independently collecting revenues from road user charges, meaning that URF still relies on inadequate quarterly releases from government to fund road maintenance activities (MoWT, 2021).

URF also lacks information on the current road condition of the unpaved National network making planning and fund allocation among agencies difficult. URF plans to establish an on-line based road maintenance management system that will incorporate agency work plans, accountabilities, road inventory and condition data (MoWT, 2021). Such a system will not be able to function without accurate road condition information which can be obtained by using the improved pavement condition assessment method proposed in this research.

Obunguta and Matsushima (2020) argue that the chronic growth of the road maintenance backlog will persist unless URF adopts a condition dependent policy instead of a time dependent policy for managing pavements. This implies that road maintenance funding allocations should be linked to road usage and condition rating. It should also be noted that although the Ugandan government has increased annual road maintenance funding over the years, the total maintenance needs have increased at an even faster rate than the increment in available funding (URF, 2022). The current available funding is only 23.9% of the total funding requirement, meaning that 76.1% of the road maintenance needs remain unmet (MoWT, 2021). This massive shortfall in maintenance funding implies that periodic maintenance activities are unfunded thereby leading to further deterioration in the condition of the road network. URF must therefore persuade government to increase funding for road maintenance so as to protect the existing road asset and also mitigate the maintenance backlog build-up. To do this, URF should first establish and validate the road inventory and condition data for the unpaved National road network.

1.3 Research Aims and objectives

The aim of this research is to:

Develop a Gravel Road Condition Index (GRCI) assessment method for unpaved roads in Uganda.

The proposed GRCI method will determine the condition rating of unpaved roads and predict future pavement deterioration. The deterioration prediction will be used to trigger maintenance and rehabilitation interventions whose funding requirements can be estimated based on the obtained GRCI value. This means that the GRCI is a road maintenance planning tool that will improve the budget allocation process of road agencies by quantifying and costing the M&R needs of unpaved roads.

This research focuses only on the Ugandan unpaved road network and was directed at achieving the following objectives:

1) To investigate current pavement condition assessment methods for unpaved roads and their related challenges.
2) To review, identify and rank the high impacting road surface distresses that affect the condition rating of unpaved roads in Uganda.

3) To develop a pavement condition assessment method, termed the Gravel Road Condition Index (GRCI), that will determine the condition rating of an unpaved road while also predicting future deterioration.

4) To validate the GRCI and its application in Uganda.

1.4 An overview of the research methodology

The research methodology is defined by Amaratunga et al. (2002) as a procedural framework for carrying out research. Chapter 4 *(Research methodology)* of this thesis discusses the research philosophy and methodology that was considered suitable for this study. Figure 1.1 summarizes the research methodology adopted for this PhD study based on the research *"onion"* model developed by Saunders et al. (2019) which was used to explain the philosophy, approach, methodological choice, strategies, time horizon, techniques and procedures deployed to achieve the objectives this study.

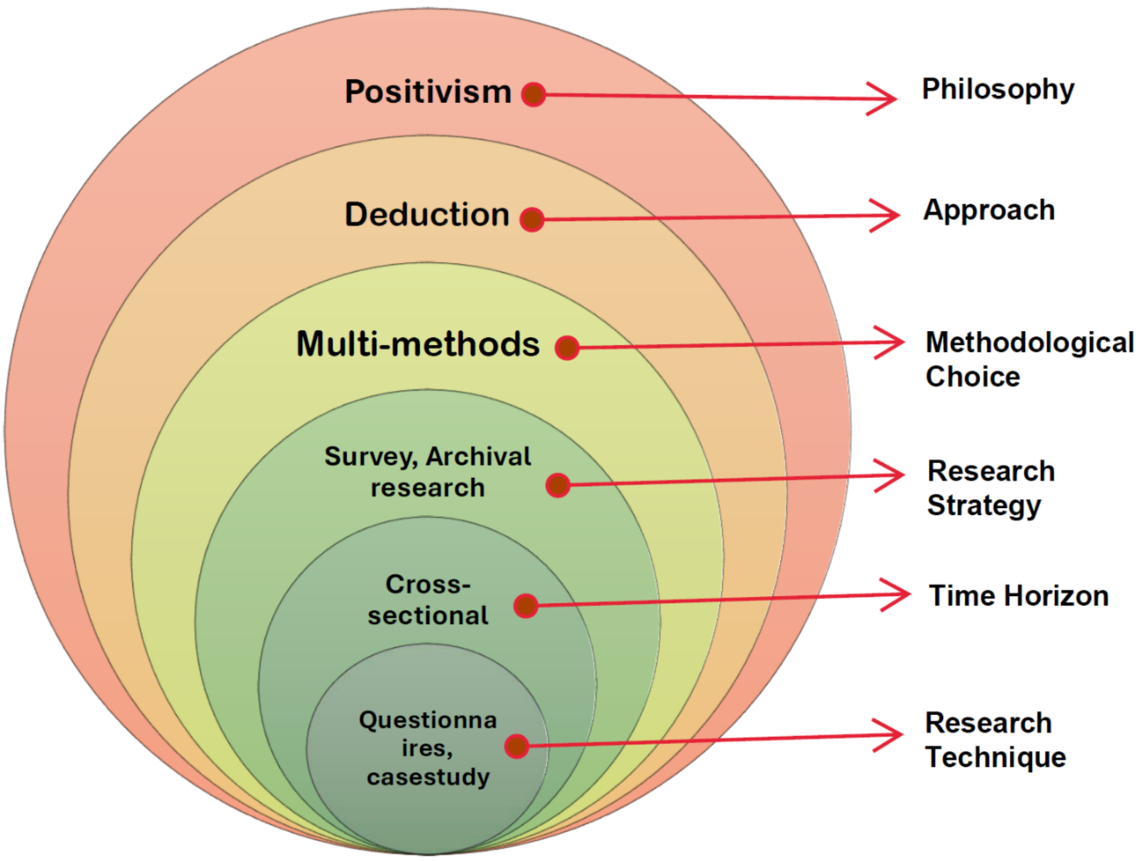


Figure 1.1: Summary of research methodology of this PhD study

The study adopted a positivist philosophical stance and deployed a deductive approach that used multi-methods during the data collection. The preferred research strategy for the study was surveys owing to the cross-sectional time horizon applicable to the study. The study also collected data by making use of questionnaires and case study-based field observation.

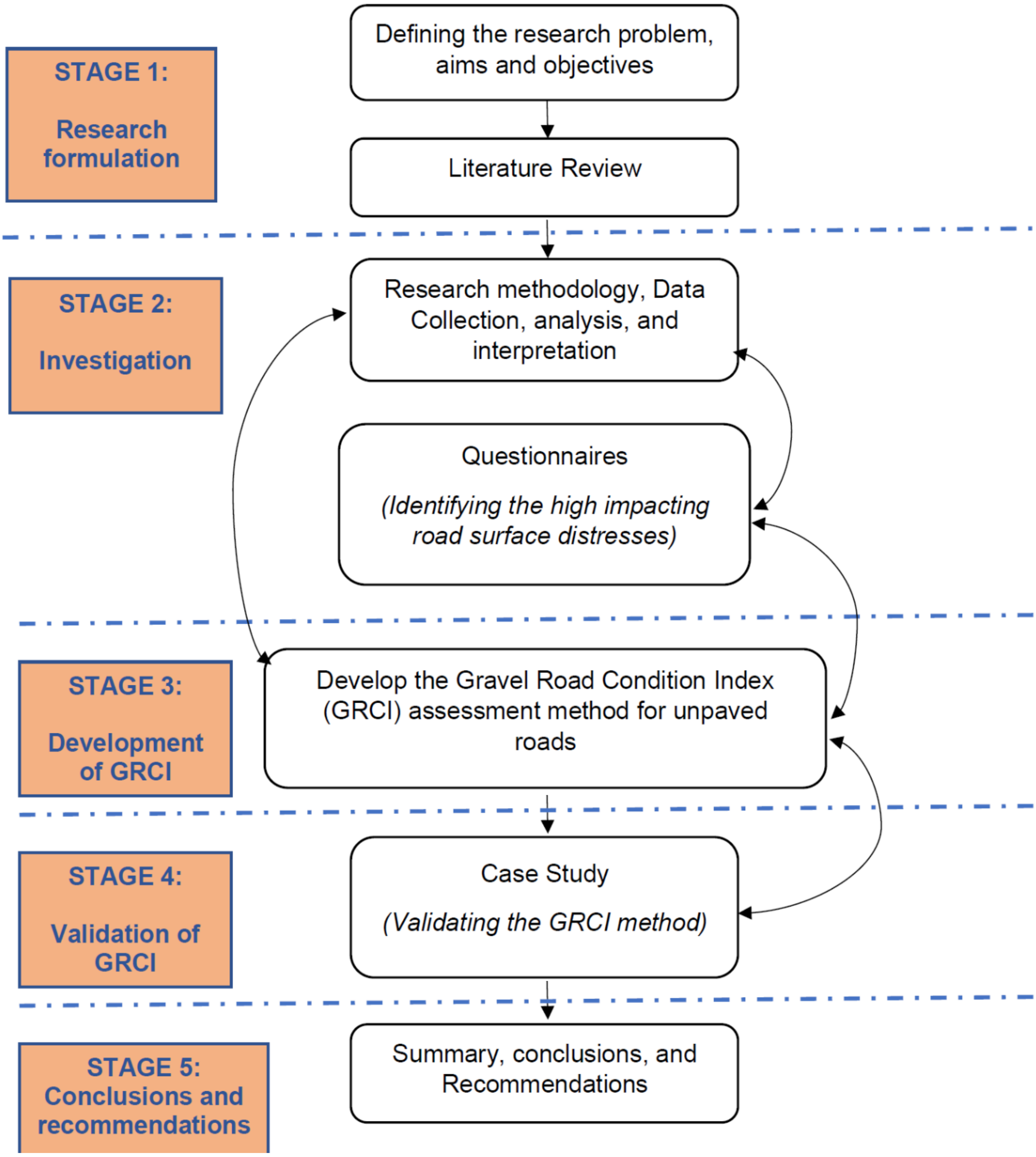


Figure 1.2: Research design of this PhD study

This research study was carried out in five (05) stages as indicated in the research design (Figure 1.2). The stages are explained as follows;

- Stage 1 *(Research formulation):* defined the research problem, aims, objectives and reviewed the existing literature regarding the concept of pavement management and PMS with particular focus on pavement condition assessment methods. The State-of-the-Art of unpaved road condition assessment and the status of pavement management in Uganda for the unpaved road network were also reviewed. This stage also reviewed the existing literature regarding prediction models for pavement deterioration.

- Stage 2 *(Investigation):* involved the use of questionnaires as the data collection method or technique. A survey was carried out for the identification of the high impacting road surface distresses on unpaved roads.

- Stage 3 *(Development of GRCI):* The data collected from industry practitioners such as road maintenance engineers and road asset managers during the survey was used to establish the weighting factor and severity combination required to develop the Gravel Road Condition Index (GRCI).

- Stage 4 *(Validation of GRCI):* involved validating the developed GRCI by applying the method on a case-study gravel road (i.e., by field observation) and verifying the results through comparison with pre-existing condition assessment methods in Uganda. The researcher also established a relationship between the novel pavement condition assessment method (i.e., the GRCI) and the gravel loss prediction model for unpaved roads in Uganda.

- Stage 5 *(Conclusions and recommendations):* summarized the findings and limitations of the study. This stage stated the conclusions and also provided recommendations for further study in pavement condition assessment methods for unpaved roads.

1.5 Contribution to Knowledge

This study attempted to fill the existing information gap regarding pavement condition assessment methods for unpaved roads by proposing an improved pavement condition assessment method termed the Gravel Road Condition Index (GRCI) for unpaved roads. This novel method advanced a more holistic understanding of the high impact surface distresses that affect the condition rating of unpaved roads. Additionally, the GRCI method addressed the lack of extensive and empirical research in unpaved road deterioration by establishing a relationship between pavement condition assessment ratings and deterioration prediction for unpaved roads. Furthermore, the process of developing the GRCI method provided useful references for further studies attempting to quantify and cost maintenance and rehabilitation interventions basing on the condition rating of unpaved roads. In practice, this study has provided a method that can effectively and efficiently determine the condition of the unpaved road network in Uganda to address the limited assessment resources and colossal backlog in condition assessment.

1.6 Research Scope

The scope of this research was to evaluate the current pavement condition assessment methods used by agencies on the Ugandan unpaved road network, it was not intended to address paved road condition assessment. This research was limited to investigating the high impacting road surface distresses and did not include the maintenance and rehabilitation interventions applicable to unpaved roads.

Furthermore, this research investigated the current application of condition assessment and was focused on optimizing the procedure for unpaved road condition assessment resulting into a fast and easy to use method that adequately enables maintenance planning for local road agencies in Uganda. Geographically, the study was conducted only in Uganda and did not cover other countries due to differences in climate, soil types, road construction methods and differing maintenance regimes.

1.7 Structure of the Research Thesis

The first chapter introduces the research including the background, problem statement, research aims and objectives, an overview of research methodology, contribution to knowledge and research scope.

Chapter two reviews the existing literature regarding pavement management and PMS with a particular focus on pavement condition assessment methods, State-of-the-

Practice of unpaved road condition assessments and the status of pavement management in Uganda for the unpaved road network.

Chapter three reviews existing literature regarding prediction models for pavement deterioration that have been developed for unpaved roads with particular emphasis on the gravel loss prediction models.

Chapter four describes the methodology adopted in developing a pavement condition assessment method and describes the data collection processes for the novel method.

Chapter five discusses the high impacting road surface distresses for the unpaved Ugandan road network identified from the survey.

Chapter six describes the development of the Gravel Road Condition Index (GRCI) assessment method for unpaved roads using the Analytic Hierarchy Process (AHP).

Chapter seven discusses validation of the GRCI through application of the method on a case-study gravel road and verifying the results through comparison with pre-existing condition assessment methods in Uganda. This chapter also details the relationship between the derived index and deterioration prediction.

Chapter eight presents the summary, conclusions, study limitations and recommendations for further research.

Chapter Two

LITERATURE REVIEW

2.1 Introduction to pavement management

Road infrastructure networks are the back-bone to a nation's economy, contributing between 3% to 5% of the GDP in developed countries (Peraka and Biligiri, 2020). Similarly, Mane et al. (2016) states that one of the essential elements for stimulating a country's economic growth is improved connectivity and accessibility of the road network. It is therefore important that this high value asset is maintained to good service levels by practicing effective pavement management.

The basic concepts of pavement management *[the process of planning the maintenance and repair of a road network or other paved facilities]* were developed in the 1960's when engineers and agencies maintained roads using a paper based system that involved the use of ledgers, strip maps and archived files. It should be noted that during this time, most road agencies in developed countries had invested heavily in the construction of new pavements and limited attention was focused on the maintenance and preservation of existing pavements (Haas, Hudson and Zaniewski, 1994). However, following the December 1970 Conference on 'Structural Design of Asphalt Pavement Systems' held in Texas, USA, engineers and road agencies realized that the idea of designing a pavement with a design life of 20 years was fictitious. Road pavements, at that time, lasted between only 10 to 12 years meaning that to attain the required 20 years, design-life, maintenance and rehabilitation interventions had to be considered at the outset. It was therefore clear that the agencies had to link the activities of planning, designing, constructing and maintaining pavements by developing a comprehensive system for managing road pavements (Haas, Hudson and Zaniewski, 1994), hence the concept of pavement management systems (PMS) was established.

This chapter starts by introducing the concept of pavement management before discussing PMS and the associated structures. Pavement condition assessments for both paved and unpaved roads are also comprehensively discussed since they are key inputs to the PMS database. This chapter also examines the distresses and causes of deterioration on unpaved roads before reviewing the State-of-the-Practice of unpaved road condition assessments. Lastly, the status of pavement management in Uganda, with a particular focus on the need for an improved condition assessment method for unpaved roads are discussed in this chapter.

2.1.1 Common Definitions

AASHTO, 2012 defines pavement management as "…*a set of tools or methods that assist decision-makers in finding optimum strategies for providing, evaluating, and maintaining pavements in a serviceable condition over a period of time."* In contrast, Alfar (2016) describes pavement management as "…*the process of planning, organising and controlling all works on the roads considered necessary to sustain a required level of service or improve the overall condition of the roads to attain a certain desired level of service".* Both definitions while slightly different, elude to the fact that pavement management in its broad sense is a process of planning the maintenance and repair of a road network or other paved facilities such as airport runways and parking lots.

As this thesis focuses on pavement management of roads, it is important to define some of the commonly used road pavement related terms as summarized in Table 2.1.

Table 2.1: Common Definitions related to road pavements

Term	**Definition**	**Source**
Pavement	The upper layers of the road comprising the selected subgrade, subbase, base, shoulders and surfacing.	Alzubaidi, (1999)
Paved road	A road with a bituminous surface, surface dressing or asphalt surface, or with a concrete or concrete block surface.	Schnebele et al., (2015)
Unpaved road	A road with a gravel or earth surface.	Schnebele et al., (2015)
Flexible pavement	A pavement with a bituminous asphalt or bituminous seal surfacing.	SAPEM, (2014)
Rigid pavement	A pavement with a concrete surfacing.	SAPEM, (2014)

The next section discusses the various aspects of pavement management and Pavement Management Systems (PMS) with emphasis on pavement condition data for both paved and unpaved roads.

2.2 Pavement Management Systems

The concept of Pavement Management Systems (PMS) can be traced back to the late 1960's and early 1970's as a result of the need to provide more cost-effective mechanisms for funding and future planning of road projects, in addition to providing lasting solutions to the countless unanticipated pavement failures to the Canadian and American road networks at the time (Haas, Hudson & Falls, 2015; Kulkarni & Miller, 2003). Haas and Hudson (1978) pioneered the use of a systems methodology in the pavement management context, and published a PMS textbook that laid the foundation to PMS that is still prevalent today. While many advances have been made to pavement management concepts, the basic structure of the pavement management process introduced by the 1978 and 1994 PMS books has largely remained intact (Haas, Hudson & Falls, 2015).

Haas, Hudson and Zaniewski (1994) define a PMS as a set of tools that assist decision-makers to find optimum strategies for providing and maintaining pavements in a serviceable condition over a given time period. Another researcher, Wells (1984), defined a PMS as "an integrated set of systematic procedures designed to assist engineers and managers in making consistent and cost-effective decisions related to the design, maintenance, and restoration of pavements." While the latter definition varies slightly from the former, it can be generally agreed that a PMS helps engineers and decision-makers to maximize the effectiveness of funds available for preservation of road pavements (AASHTO, 1990). Simply put, a PMS supports the maintenance of pavements at sufficient serviceability levels through a systemized optimization of the limited available funds. Zagvozda et al., (2019) suggests that PMS's have, in recent times, also been referred in the literature as Pavement Maintenance Management Systems (PMMS). These systems are also used in the management of pavement maintenance, and for the purpose of this thesis, the term 'PMS' will be used. Figure 2.1 illustrates the two decision levels of a PMS i.e., network level and project level.

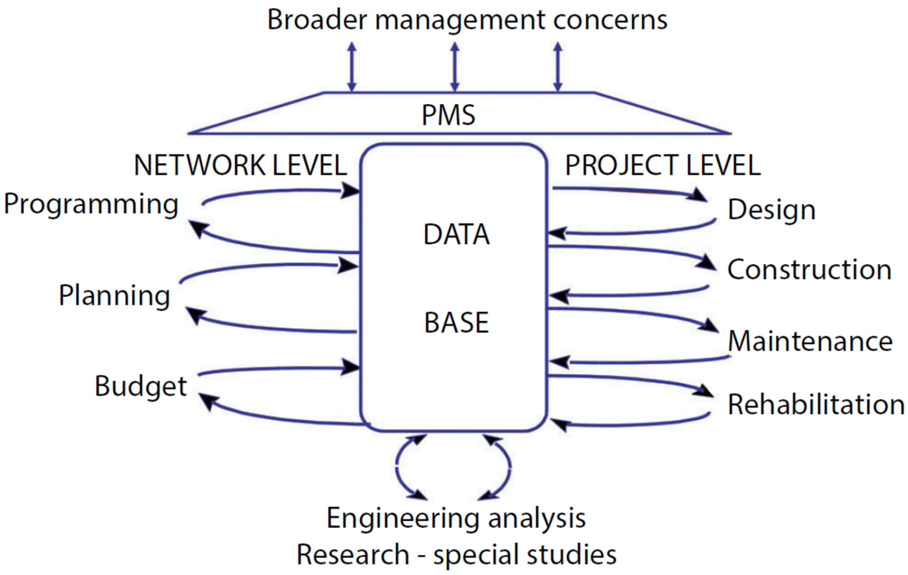


Figure 2.1: Major components of a PMS (Haas, Hudson & Falls, 2015)

Network level decisions of a PMS cover the policy and programming aspects of pavement management. These include identifying priorities, developing pavement preservation policies, determining funding needs and budget allocations for maintenance and rehabilitation (M&R) of the entire road network (AASHTO, 1990). Project level decisions on the other hand, address the engineering and technical aspects of site-specific or section-specific pavement management. These decisions are normally determined on an individual project level after the network level M&R needs have been identified. The project level PMS considers additional M&R for individual road segments and prioritizes the minimalization of pavement life cycle costs (AASHTO, 1990).

The PMS components shown in Figure 2.1 mutually interact: covering planning, programming, budgeting, design, construction and M&R. For a well-developed PMS, the components and database should effectively interact in order to produce a *"value for money"* system that is practical, adaptable and provides good feedback information for decision makers (Haas, Hudson and Zaniewski, 1994).

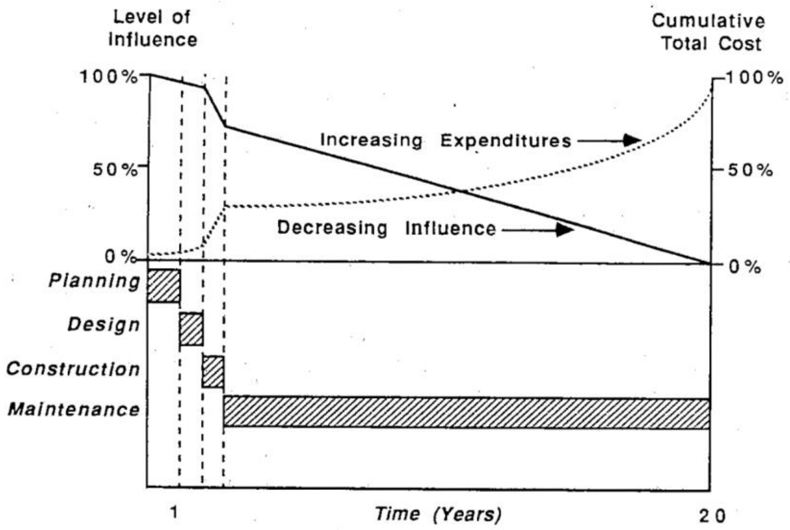


Figure 2.2: Influence Level of PMS components on the Total Costs (Haas, Hudson and Zaniewski,1994)

The “level of influence” of the four major PMS components (i.e., planning, design, construction and M&R) change, with varying cost impacts, during the total lifecycle of a pavement. Figure 2.2 illustrates that the planning, design, and construction components are merely a fraction of the total life-cycle cost with M&R consuming the largest proportion of the funds (Haas, Hudson and Zaniewski, 1994). This simplified illustration of the entire lifecycle of a pavement in Figure 2.2, clearly shows the importance of informed decision-making during the planning and design phases when the level of influence of these components is still high. Since the expenditure is low during these phases, it is important that decisions and commitments made are systematic and well managed because they have far greater influence on the expenditures required during M&R (Mubaraki, 2010).

It is also important to note that in recent times, researchers like Zagvozda et al., (2019) have developed PMS structures that incorporate these major PMS components. Section 2.3 discusses the various PMS structures that are used to effectively manage the M&R needs of a road network.

2.3 PMS Structures

A number of studies have presented various PMS structures that are fundamental in establishing an effective PMS. Zagvozda et al., (2019) assert that a PMS structure consists of pavement condition surveys, a road network database, performance models, a decision aid tool, quality evaluation tool, and analytical models that predict future cost needs. The PMS structure shown in Figure 2.3 provides the necessary information to adequately manage the M&R needs of a road network. In contrast, AASHTO (2012) suggests a structure with six key elements i.e., inputs, database, analysis parameters, analysis module, reporting module and a feedback loop. The inputs include general inventory information such as road location, road age, road width, pavement type and the traffic volume. The condition of the pavement, both current and historic, are also key inputs.

The database on the other hand makes use of technology to store, sort and retrieve condition information. This data storage can range from simple spread sheets to complex data storage computers (AASHTO, 2012). Peterson (1987) supports the understanding that the database contains systematic techniques of collecting and storing information. It can therefore be agreed that data storage is an important element of the PMS structure that should deploy a data storage method relevant to the needs of the agency. Some agencies rely on Geographical Information Systems (GIS) to store and retrieve road network data (AASHTO, 2012).

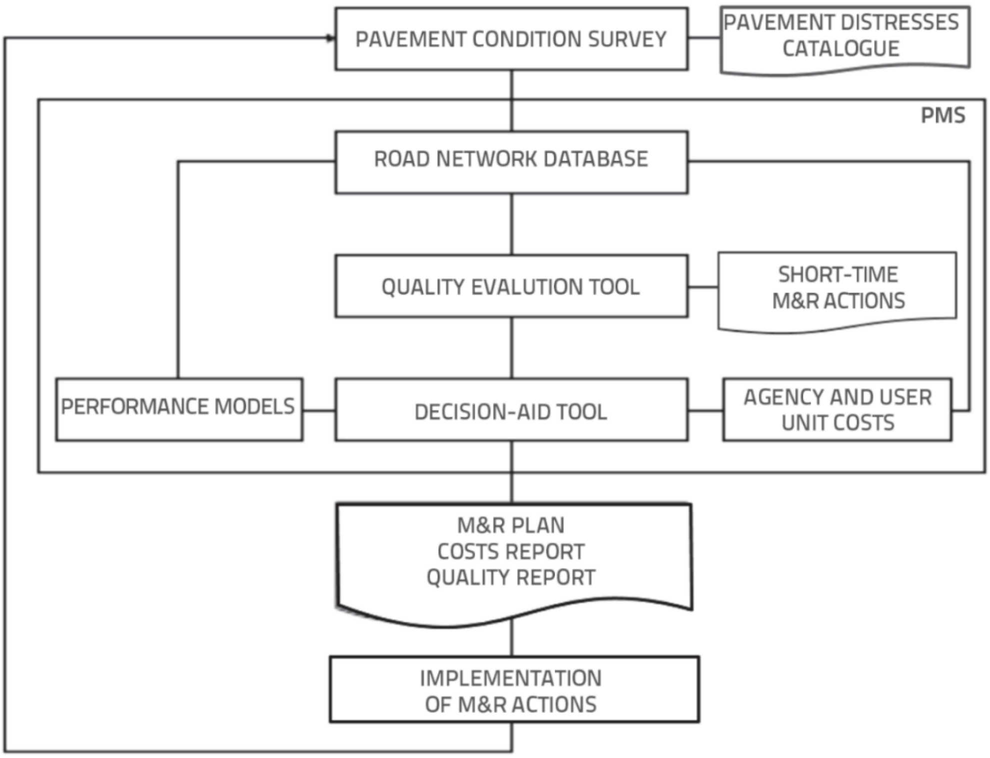


Figure 2.3: PMS Structure (Zagvozda et al., 2019)

The analysis scheme by Peterson (1987) comprises of algorithms that interpret pavement condition information in a logical way making use of deterioration models to establish future M&R needs. This is similar to AASHTO (2012) which states that the analysis parameters shown in Figure 2.4 include pavement deterioration models that provide the basis for predicting future pavement conditions of the road network. These models are critical in establishing future funding needs and enable agencies determine which M&R activities will be required at what time. As such, analysis models are pivotal to the efficient functioning of a PMS because of their ability to quickly process and analyse data that gives decision makers options on which treatment methods will lead to the optimized use of available funds.

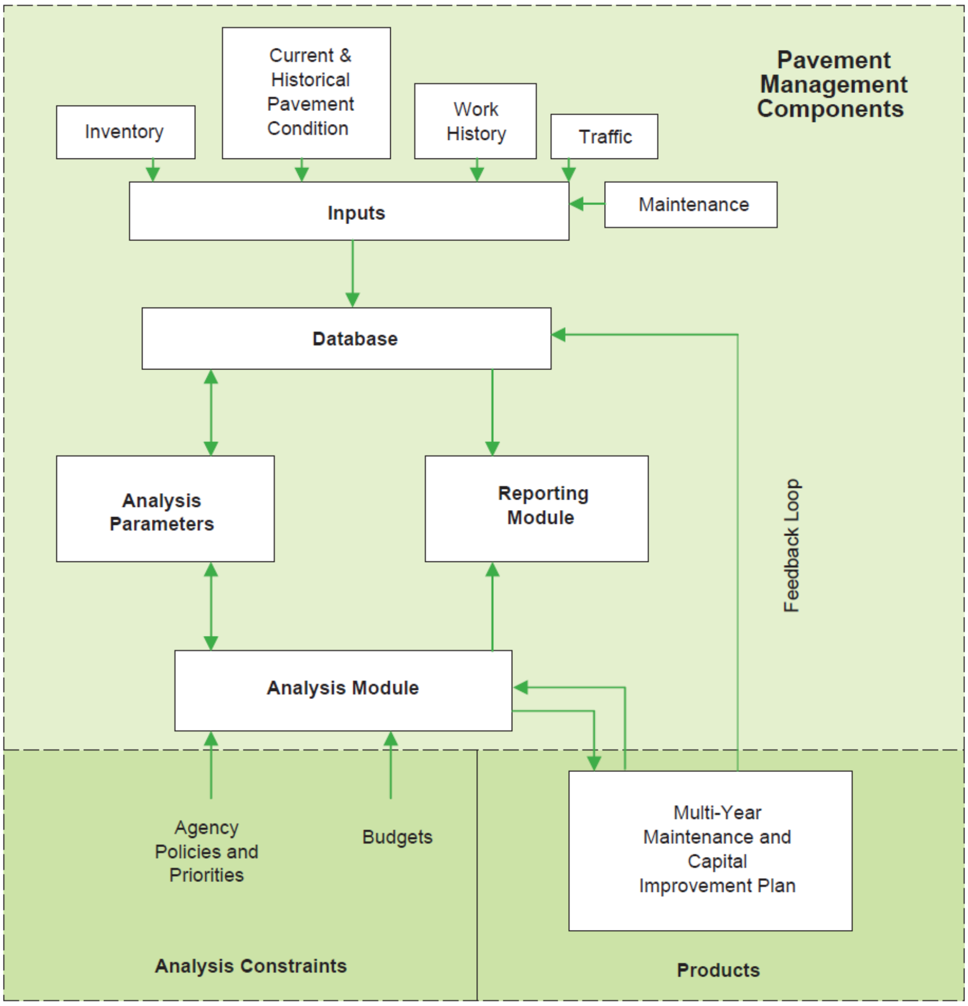


Figure 2.4: PMS Structure/Components (AASHTO, 2012)

AASHTO (2012) describes the reporting module of a PMS as a reporting function that provides users with various types of reports regarding the road network. Accessibility to this information has in recent years drastically improved due to the emergence of GIS based PMS's. It should however be noted that the level of reporting is dependent on the sophistication of the PMS. Simpler spreadsheet-based PMS's may not be able to produce a wide variety of report formats.

The feedback process in any system is important because it verifies and improves the reliability of a PMS. Both AASHTO (1990) and AASHTO (2012) attach similar importance to the feedback process because it compares the actual costs of the M&R activities to those derived from the PMS at the planning stage. The feedback process also compares the field observed pavement conditions with those predicted by the PMS models. Such information is key to understanding the primary mechanisms causing pavement deterioration and assessing whether the recommended M&R treatments were appropriate.

It should be noted that data collection and database creation is essential for the development of an efficient PMS. This is due to the fact that all other components and/or elements are generated from the database and as such, care should be taken when selecting the type and quantity of data required (Zagvozda et al., 2019). The focus of this research, therefore, is mainly on the PMS data collection process with emphasis placed on pavement condition information.

2.4 Pavement condition assessments for paved roads

One of the key inputs to the PMS database is data on both current and historic pavement conditions. This information is obtained through pavement condition assessments defined as a processes of collecting and analyzing several indicators of the pavement condition (AASHTO, 2012). Zimmerman (2011) contends that acquiring pavement condition data is an expensive and time-consuming activity, however, he adds that it is arguably the most important step in developing a workable and efficient PMS.

AASHTO (2012) suggests that the pavement condition data required by road agencies should be divided into three main broad categories: 1) surface distresses, 2) structural capacity and 3) surface characteristics. Haas et al. (2015) similarly proposes four categories of pavement condition data i.e., 1) structural capacity, 2) condition, 3) performance, and 4) safety of the pavement. The following review however focuses on the functional performance of flexible pavements, categorized into two aspects i.e., surface distresses and surface roughness. These two aspects are reviewed because they physically manifest on the surface of a pavement and are thus easy to observe and measure thereby providing timely information on the condition of the pavement. Technical data, such as structural capacity and safety requires test equipment, which significantly impacts time and cost required for the condition assessment. Whilst still important to undertake, structural capacity data is not superior to surface distress and roughness data in determining the condition of a pavement.

2.4.1 Surface Distresses

Road pavements undergo deterioration over time due to traffic loading and environmental factors, leading to the development of distresses within the pavement. These visible distresses can be measured and catalogued during pavement condition surveys to identify the nature, severity, and extent of these distresses (TRL, 1998). Haas and Hajek (1990) define pavement distresses as visible manifestations of numerous mechanisms that lead to a reduction in pavement performance. Research carried out by Haas and Hajek (1990) identified 15 pavement distresses that could be used to determine the pavement condition. The study also revealed that the distresses were due to pavement deterioration and as such interrelated, with many of the distresses having high statistical correlations.

More recent research into surface distresses carried out by Miller and Bellinger (2014) led to the development of the *Distress Identification Manual for the Long-Term Pavement Performance Program (DIM)* of the U.S. Federal Highway Administration. This manual is widely used by road agencies in the U.S. and around the World to identify and classify surface distresses. The fifth edition of the DIM groups 15 distress types into five major categories i.e., cracking, patching and potholes, surface deformation, surface defects and miscellaneous distresses. Flamarz Al-Arkawazi, (2017) similarly categorizes surface distresses into four major groups i.e., cracking, surface deformation, disintegration, and surface defects. He also describes the possible causes of each individual distress summarized in Table 2.2. It should also be noted that the causes of distresses identified by Flamarz Al-Arkawazi, (2017) are similar to those mentioned by Miller and Bellinger (2014) in the DIM.

Table 2.2: Common flexible pavement distresses and their possible causes (Flamarz Al-Arkawazi, 2017)

S/N	Failure Type	Expected or Possible Causes
1.	Alligator cracking	• Fatigue failure due to flexible/brittle base. • Inadequate pavement thickness.
2.	Block cracking	• Reflection of joints cracking in underlying base.
3.	Longitudinal cracking	• Reflection cracking. • Poor paving lane joint. • Pavement widening. • Cut/fill differential settlement. • Fatigue failure of asphalt concrete.
4.	Transverse cracking	• Reflection of shrinkage cracking. • Construction joints.
5.	Rutting	• Inadequate pavement thickness. • Post construction compaction. • Instability of base surfacing.
6.	Shoving	• Poor bond between layers. • Lack of edge containment. • Inadequate pavement thickness.
7.	Depressions	• Settlement of service trench or embankment. • Isolated consolidation. • Volume change of subgrade
8.	Corrugations	• Instability of asphalt concrete or base course.
9.	Edge drop	• Inadequate pavement width. • Erodible shoulder material (lack of plasticity).
10.	Edge break	• Inadequate pavement width. • Inadequate edge support. • Traffic travelling on shoulder edge drop. • Weak seal coat/loss of adhesion.
11.	Raveling	• It is a result of insufficient adhesion between the asphalt cement and the aggregate. • Initially, a fine aggregate break loose and leaves small, rough patches in the surface of the pavement.
12.	Potholes	• Potholes are often located in areas of poor drainage. • Potholes are formed when the pavement disintegrates under traffic loading, due to inadequate strength in one or more layers of the pavement, usually accompanied by the presence of water.
13.	Polishing	• Caused by traffic movement (vehicles movement).
14.	Patches	• Filling the holes with asphalt concrete without cleaning and preparing and doing the required works for maintenance. • Filling the holes without doing proper leveling and compaction.

The surface distresses highlighted in Table 2.2 can be measured and catalogued through pavement condition surveys *(see section 2.4.2).*

2.4.2 Pavement Condition Surveys

Pavement condition surveys are an important component of pavement maintenance management because they provide critical information about the current condition of the road network and enable informed decision-making regarding M&R strategies. These surveys involve the systematic assessment of various pavement characteristics, such as cracking, rutting, raveling, and surface distress, to evaluate the overall condition of the road surface (Saluja et al., 2021;Singh et al., 2018; AASHTO, 2012). Effective pavement condition surveys are essential for maintaining a safe and efficient road network. They enable road agencies to prioritize maintenance and rehabilitation activities, allocate resources effectively, and ensure the long-term performance of the road infrastructure.

Pavement condition surveys are broadly categorized into visual or automated surveys that can be conducted using manual visual assessments or advanced automated technologies respectively (Saeed et al., 2020). Manual assessments can be labor-intensive and time-consuming but can provide detailed pavement condition data, allowing for the identification of specific types of distresses and their severity (Saluja et al., 2021). Manual surveys involve the use of trained raters that visually assess the pavement condition and record the observed distresses. These surveys can be conducted on foot or from a moving vehicle and while they are relatively simple to use and cost-effective, visual surveys can be subjective and prone to human error (Saluja et al., 2021). Automated surveys, on the other hand, leverage various sensors and computer vision techniques to collect objective, quantitative data on pavement condition, often at higher speeds and with greater efficiency (Saeed et al., 2020). One approach to automated pavement condition surveys involves the use of conventional sensors, such as accelerometers and laser profilers, mounted on vehicles to measure road roughness and other pavement characteristics (Saeed et al., 2020). These systems can continuously collect data as the vehicle travels, offering a comprehensive assessment of the road network. Additionally, an emerging technique utilizes cost-effective devices, such as smartphones or dashcams, to capture video or audio data, which can then be analyzed using intelligent algorithms to detect road distresses and assess pavement condition (Saeed et al., 2020).

One of the primary objectives of pavement condition surveys is to determine an overall value of the pavement's condition, typically using a standardized rating system or index (Saluja et al., 2021). Pavement condition indices are described by Attoh-Okine and Adarkwa (2013) to include data collection, condition rating and data quality management. These activities are performed to inform agencies of the serviceability and physical condition of the pavement. Additionally, AASHTO (2012) asserts that the selection of a pavement condition index depends on the agency needs and also on the type of pavement condition data available. In contrast, Attoh-Okine and Adarkwa (2013) believe that the pavement condition index selected is dependent on the funds and resources available to the agency as well as the index's ability to address the localized pavement performance needs of the agency.

AASHTO (2012) distinguishes the pavement condition indices into two types: 1) composite indices, 2) individual indices. The difference between the two is that composite indices aggregate multiple surface distresses observed during condition surveys into a single overall index while individual indices are obtained for a single type of pavement distress. Papageorgiou (2019) argues that because individual indices asses only one pavement feature, they do not give an accurate assessment of the overall pavement condition and as such are more likely to mislead decision-makers. He however adds that individual index data may provide an indication of the extent of maintenance activities required for a particular type of distress. Both composite and individual indices commonly used by agencies are discussed in the following sections, including:

- Pavement Condition Index (PCI)
- Present Serviceability Index (PSI)
- International Roughness Index (IRI)
- Pavement Surface Evaluation Rating (PASER)
- Course and Detailed Visual Inspections (CVI & DVI)

2.4.2.1 Pavement Condition Index

The Pavement Condition Index (PCI) is a composite rating procedure developed by the U.S. Army Corps of Engineers in 1976, and is still widely used in the U.S. and Canada to rate the condition of pavements (Ali et al., 2023; Attoh-Okine and Adarkwa, 2013). It was published by the American Society for Testing and Materials (ASTM) documented in ASTM D6433 *[Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys]* (Loprencipe and Pantuso, 2017). According to Ali et al. (2023), PCI is the most commonly used index for evaluating pavements based on visual inspections. This rating procedure has been adopted as a standard procedure by many agencies worldwide, including for pavements in developing countries. Chile, for example, developed the Urban Pavement Condition Index (UPCI) using the PCI for the assessment of Chilean urban pavements. The UPCI developed new guidelines for identifying and measuring distresses that are not included in ASTM D6433, such as manhole covers and catch basins, which are specific to urban road pavements (Loprencipe and Pantuso, 2017). Other countries have also developed different methods of combining distress index equations by applying a limited and predefined number of distresses stated in ASTM D6433. India in particular has developed a bespoke version of the PCI by assigning different weights to each observed distress (Loprencipe and Pantuso, 2017). It is therefore important to note that the PCI is one of the most widely used pavement condition rating system in the World.

PCI measures the pavement integrity and surface distress condition based on a numerical scale from 100 to 0 i.e., from Good to Failed as shown in Figure 2.5. PCI is a manual visual condition assessment method that identifies each distress and assigns a value based on the distress; type, severity, and extent. The weighted average of the PCIs for multiple sub-sections is then the condition of the entire section (Attoh-Okine and Adarkwa, 2013).

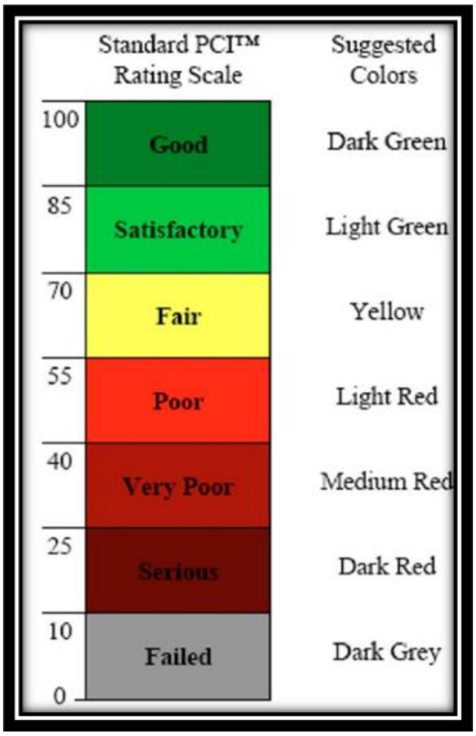


Figure 2.5: PCI Rating Scale and Suggested Colors (ASTM, 2007)

It should be noted that PCI does not measure skid resistance, structural integrity, or the roughness of a pavement (ASTM, 2007). PCI, however, provides agencies with a well-established rational against which maintenance activity prioritization can be made for pavements. Agencies are encouraged to continuously monitor the PCI values of pavements at project and network levels to predict future maintenance needs for timely identification and treatment of surface distresses (ASTM, 2007). Ragnoli et al. (2018) notes that although PCI generates accurate and consistent results, it involves a very labour intensive and time-consuming manual data collection process.

2.4.2.2 Present Serviceability Index (PSI)

The Present Serviceability Rating (PSR) is one of the earliest pavement condition rating systems developed by the AASHO Road Test programme in the 1960's. PSR is a subjective condition rating that deploys the use of trained raters riding in a vehicle and assign a pavement condition value from 0 to 5, i.e., Very Good to Very Poor (Carey Jrand Irick, 1960). Because PSR is a subjective rating, researchers Carey and Irick (1960) developed a method of converting the PSR into an objective index. This was done by relating measurable pavement distresses such as cracking, rutting and roughness to the PSR, the result of which was the Present Serviceability Index (PSI). At the time, creation of an objective pavement condition index was considered a remarkable achievement because the PSI was a more reliable pavement condition measurement than the PSR (Carey and Irick, 1960).

In recent times, a number of researchers have developed methods of relating the Present Serviceability Rating to the Pavement Condition Index. Bryce et al. (2019) developed a model that relates PSR to PCI for flexible pavements. The research also noted that PSR data was required for road pavements carrying traffic at less than 64km/hr and as such the PSR and PSI rating system will in the near future become obsolete due to increased design speeds.

2.4.2.3 International Roughness Index (IRI)

The International Roughness Index (IRI) is an objective, individual index that is widely used all over the World to measure the functional performance of a pavement. IRI was developed by the World Bank in 1986 after the International Road Roughness Experiment (IRRE) conducted in Brazil in I982 (Sayers, 1995). While AASHTO (2012) states that IRI measures the roughness of a pavement surface and is an effective method for assessing the condition and performance of a road network, Rashid and Tsunokawa (2008) argue that a lot more research needs to be undertaken to improve the accuracy of roughness measurements.

Ragnoli et al. (2018) reports that IRI provides a ride quality classification in terms of the pavement longitudinal profile travelled by a vehicle wheel path. Sayers (1995) likewise notes that IRI is computed from a single longitudinal profile at a simulated vehicular speed of 80km/hr. IRI values are reported in meters per kilometer (m/km) or inches per mile (in./mi) with a perfectly smooth pavement surface obtaining a score of zero (0) which means that a high IRI value translates into a poor pavement condition. Figure 2.6 illustrates the approximate range of IRI values on different types of road pavements.

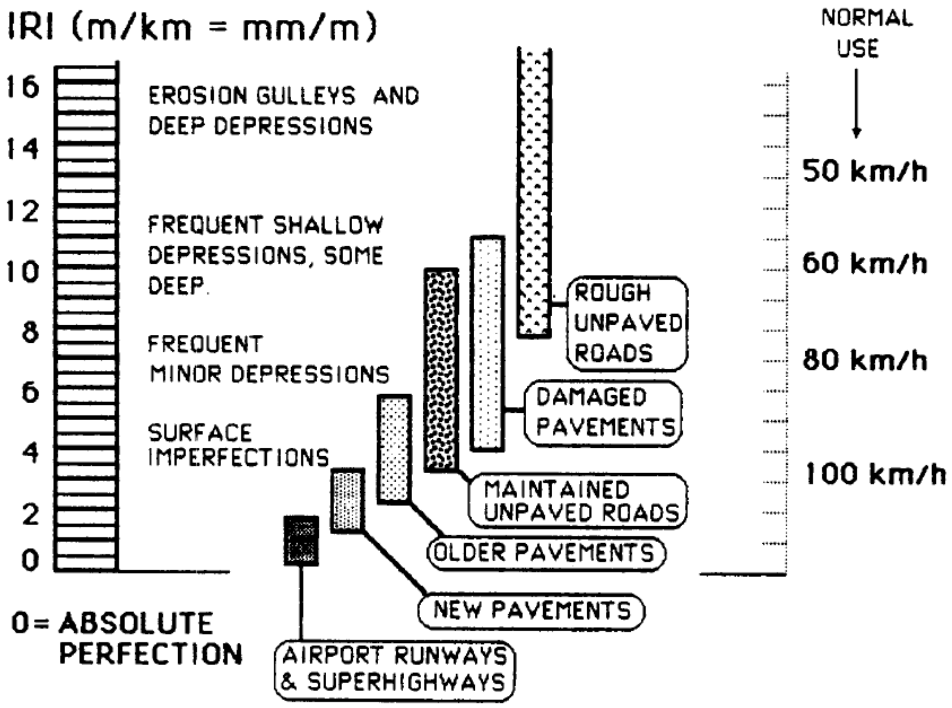


Figure 2.6: The IRI roughness scale (Sayers et al., 1986)

IRI is measured by different types of equipment categorized into four classes: Class 1 *[Precision profiles],* Class 2 *[Profilometric methods],* Class 3 *[IRI by correlation]* and Class 4 *[Subjective rating]* (TRL, 1998). Class 1 devices are the most accurate and include laser and walking profiler equipment while Class 4 measurements are the least accurate due to their subjective nature. Class 4 measurements involve rideability and visual assessments that heavily rely on the experience of the rater and as such have varying results when repeated (TRL, 1998). According to Tsunokawa and Rashid (2008), Response type road roughness measuring systems (RTRRMSs) which are Class 3 devices, are widely used because they collect roughness data rapidly and cover lengthy pavement sections as compared to equipment in Class 1 and 2.

RTRRMSs are frequently mounted onto vehicles to record roughness data as the vehicle moves along the pavement. Some RTRRMSs require that a vehicle maintains a speed of over 40km/hr while recording data, this is easier said than done because these vehicles encounter traffic stops and traffic jams during the pavement assessment (Tsunokawa and Rashid, 2008). This “stop-start” affects the quality of data recorded. TRL (1998) suggests that regular calibration of RTRRMSs is essential to ensuring the reliability of the data collected. Additionally, Tsunokawa and Rashid (2008) suggest that more research is needed to improve and eliminate the errors in pavement roughness data due to varying vehicles speeds. As such, they have developed calibration equations aimed at eliminating these inaccuracies in roughness data collection. Dela Cruz et al. (2021) also suggest that the challenge of the inaccuracies between the number of vehicle wheels need to be addressed through conducting further research studies in the calibration of RTRRMSs.

Even though IRI is a globally accepted and widely used index for assessing the condition of pavements, it still has several inefficiencies in data collection. According to TRL (1998) IRI is unable to identify the nature, extent and severity of observed pavement distresses, which makes IRI inferior to other more detailed indices such as PCI. However, IRI will remain one of the most popular methods for assessing lengthy pavement sections within a limited budget. It is also important to note the tremendous advancement made by researchers in having IRI measured by smartphones. In the near future, the accelerometers and GPSs that are pre-installed in modern smartphones will efficiently record IRI values for road networks (Wang et al., 2020).

2.4.2.4 Pavement Surface Evaluation Rating (PASER)

The Pavement Surface Evaluation Rating (PASER) is a subjective, composite rating procedure that is specifically suited for small local agencies with limited resources (Montgomery and Haddock, 2019). PASER was developed by the Wisconsin Transport Information Center (T.I.C) and is a pavement condition rating method that provides a simplified system of visually rating a pavement on a scale of 10 to 1 i.e., Excellent to Failed (Walker, 2013).

According to Montgomery and Haddock (2019), PASER ratings can be categorized according to three common maintenance treatments: 1) PASER ratings of 8 to 10 are *"good"* and indicate that the pavement requires limited routine maintenance activities like cleaning and crack sealing. 2) Pavements with a rating of 5 to 7 are considered *"fair*" requiring preventive maintenance activities such as thin overlays, crack sealing and seal coats. 3) The third category rating between 1 to 4 considers that a *"poor"* pavement constitutes visible structural failures which require extensive maintenance and rehabilitation treatments like patching, structural overlays or even re-construction of the entire pavement. Walker (2013) in contrast categorizes the ratings into 4 major groups i.e., Excellent (7 to 10), Good (5 to 6), Fair (3 to 4), Poor (1 to 2).

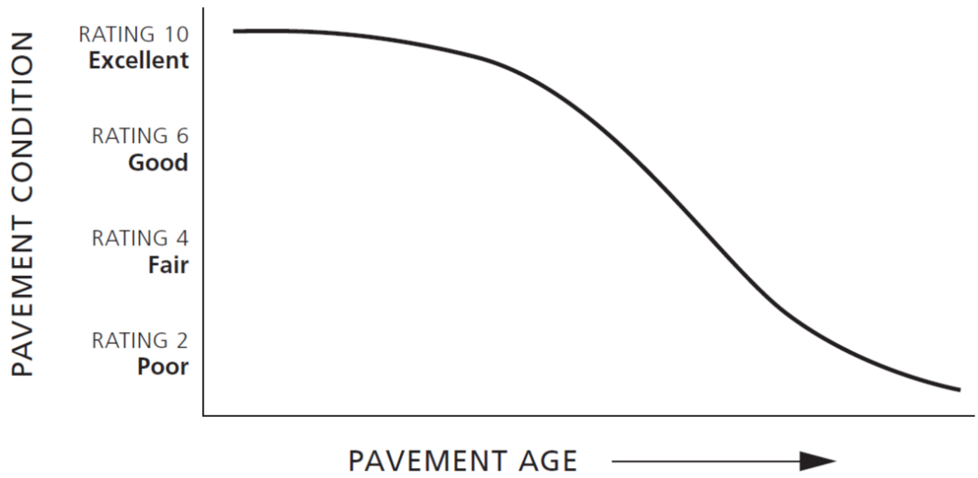


Figure 2.7: Pavement Condition Vs Age (Walker, 2013)

Walker (2013) contends that once deterioration starts, the condition of a pavement declines rapidly as shown in Figure 2.7. He adds that the sharp decline in the condition as a pavement ages is due to a combination of traffic loading and moisture penetration into the pavement layers. The pavement condition photograph examples included the PASER manuals assist raters during condition rating field exercises because they provide a reference benchmark of the condition rating required for any section of the pavement. Montgomery and Haddock (2019) argue that although PASER follows a well-defined criterion, its visual nature and reliance on the experience of a rater make PASER a subjective and variable rating system. It is because of this that Walker (2013) emphasizes the need to improve the training and guidelines provided to raters for determining the PASER values of assessed pavements.

2.4.2.5 Course and Detailed Visual Inspections (CVI & DVI)

According to Radopoulou and Brilakis (2017), most agencies in the UK assess pavements using manual visual surveys. This is evidenced by the weekly manual inspections carried out by accredited inspectors on the primary road network. Rahman et al. (2023) add that among the various manual visual inspections, the Coarse Visual Inspection (CVI) and Detailed Visual Inspection (DVI) are the predominant visual assessment methods used to determine the condition of the unclassified road networks in the UK.

Being a rapid *“windshield”* survey, requires that CVI is carried out in a slow moving vehicle by an accredited inspector (DfT, 2019). O’Flaherty (2002) states that the CVI was originally designed as a rapid low-cost network survey that would be used to identify sections in the road network requiring detailed assessments. He however adds that CVI has recently become the default network monitoring tool used by most agencies for Non-Principal roads in the UK. DfT (2019) also notes that CVI data can easily be uploaded into the UKPMS because the file format of CVI data is compatible with the UKPMS.

DVI on the other hand is an on-foot visual assessment carried out at targeted locations by an accredited visual inspector (Rahman et al., 2023; O'Flaherty, 2002). Similarly, DfT (2019) contends that DVI is carried out on sections identified as defective by other pavement condition assessment methods such as CVI. This implies that DVI is a more detailed and time-consuming inspection which in practice is used on urban networks. Rural agencies prefer CVI over DVI because it requires less resources (O'Flaherty, 2002).

Table 2.3 Comparison between pavement condition indices for paved roads

Pavement Condition Index	Advantages	Disadvantages	Sources
Pavement Condition Index (PCI)	• Objective measured index. • Measures pavement integrity and surface distress condition based on a numerical scale from 100 (Good) to 0 (Failed). • PCI generates accurate and consistent results.	• Very labour intensive. • Time-consuming manual data collection process.	Ali et al. (2023), Loprencipe and Pantuso (2017), Attoh-Okine and Adarkwa (2013)
Present Serviceability Index (PSI)	• Visual assessment with 5-point rating scale of 0 (Very Good) to 5 (Very Poor).	• Subjective index. • Required for road pavements	Bryce et al. (2019), Carey and Irick (1960)

Pavement Condition Index	Advantages	Disadvantages	Sources
		carrying traffic at less than 64km/hr.	
International Roughness Index (IRI)	• Objectively measures roughness. • Globally accepted and widely used index for assessing the condition of pavements. • Measures functional performance of a pavement	• Requires specialised equipment mounted onto vehicles to record roughness data. • The specialised equipment is expensive to purchase.	Dela Cruz et al. (2021), Wang et al. (2020), Tsunokawa and Rashid (2008), Sayers (1995)
Pavement Surface Evaluation Rating (PASER)	• Suitable for small local agencies with limited resources. • Simplified system of visually rating a pavement on a scale of 10 to 1 i.e., Excellent to Failed.	• Subjective index. • Heavily relies on assessor's experience in distress identification.	Montgomery and Haddock (2019), Walker (2013)
Course and Detailed Visual Inspections (CVI & DVI)	• CVI is a rapid "windshield survey" index. • CVI is a low-cost network index. • CVI data can easily be uploaded into the UKPMS.	• Requires an accredited visual inspector. • DVI requires a more detailed and time-consuming inspection.	Rahman et al. (2023), Radopoulou and Brilakis (2017), O'Flaherty (2002)

2.5 Distresses of unpaved roads

Unpaved roads are at times referred to as gravel or unsealed roads by some researchers and are composed of natural granular materials (Saeed et al., 2020).

Aleadelat and Wright (2018) state that unpaved roads normally carry less traffic than paved roads and are usually managed by smaller local agencies with limited budgets. They add that while unpaved roads formulate more than 90% of local networks in developing countries, research into their distresses is limited. Walker (2002) argues that this is because the pavement condition of unpaved roads rapidly changes due to traffic and precipitation. The condition of an unpaved road can change literally overnight and as such researchers have found it difficult to carryout significant studies on their distresses. That said, a number of unpaved road distresses have been identified by Cudworth and Rahman (2023), Alzubaidi (1999), CSIR (2000), Walker (2002), USACE (1995), and Brooks et al. (2011) discussed in the following passages, including:

- Camber loss
- Inadequate drainage
- Inadequate gravel thickness
- Surface deformation:
    - *Corrugations*
    - *Potholes*
    - *Rutting*
    - *Erosion gullies*
- Dust
- Loose gravel
- Stoniness

2.5.1 Camber loss

According to Alzubaidi (1999), the transverse shape or camber or crown of an unpaved road is the most important maintenance feature. This is because having adequate camber eases water drainage off a road's surface quickly thus avoiding ponding. Similarly, Walker (2002) also suggests that in order to quickly drain water off the road surface, the camber should be built at least 150mm above the shoulder edge to obtain an adequate crossfall as illustrated in Figure 2.8. It should also be noted that the camber of unpaved roads is significantly greater than that of paved roads.

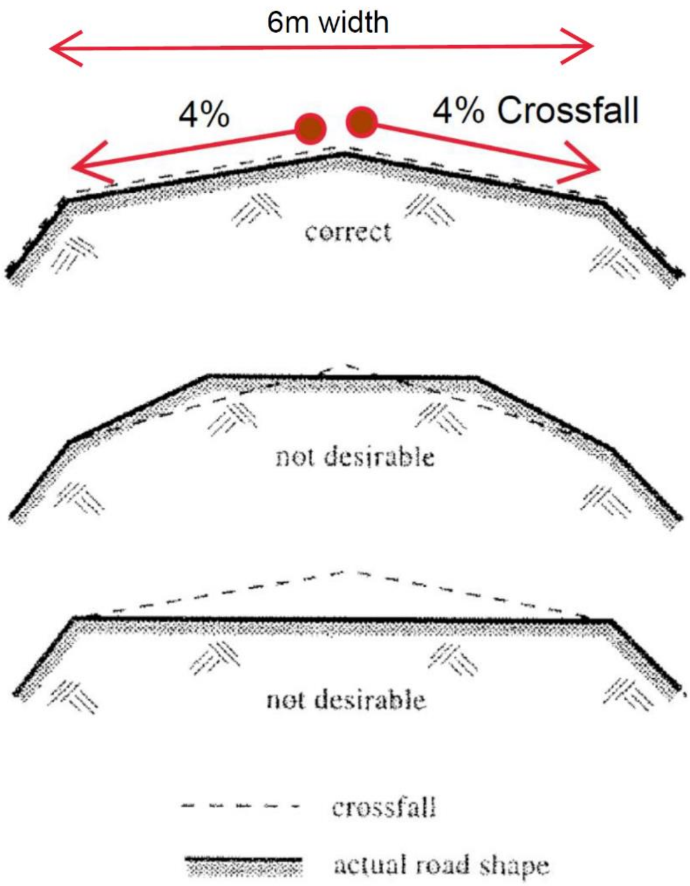


Figure 2.8: Examples of adequate and inadequate camber (Alzubaidi, 1999)

USACE (1995) however suggests that no camber is required at curve sections because unpaved roads are usually banked to one side at these sections. The importance of having a correct camber cannot be overstated because ponding softens the subgrade and roadbed layers leading to rapid road deterioration under traffic (Walker, 2002). It is therefore important to restore camber loss by re-grading using a motor grader (Cudworth and Rahman, 2023). Excessive camber loss on the other hand, may require complete re-working of the road surface by scarifying and re-processing the surface gravel material (Walker, 2002). It should be noted that by carrying out M&R activities to correct the camber, other surface distresses such as potholes, ruts and corrugations are also consequently repaired during the activity.

2.5.2 Inadequate drainage

Roadside ditches or side drains are very important in draining water away from the road pavement. Alzubaidi (1999) notes that water can be very destructive to unpaved roads and as such a functioning drainage system is required to prevent ponding and erosion of roadside slopes. USACE (1995) developed a distress measurement guide for roadside drainage based on three severity levels shown in Figure 2.9 i.e., Low, Medium, and High. The low severity relates to a road condition with small amounts of ponding and debris while high severity indicates excessive ponding, overgrowth and debris in the side drains and erosion into the road shoulders. In contrast, CSIR (2000) measures drainage from the road on a five-point scale with one (1) indicating that the road is well above the ground with adequate drainage while five (5) relates to a road below the ground level and as such is classified as a canal with absolutely no drainage system. M&R activities such as clearing of vegetation and debris in the side drains need to be carried out periodically to maintain the functionality of the drainage system (Walker, 2002).

While USACE (1995) and CSIR (2000) only assess the condition of side drains, Walker (2002) on the other hand takes drainage across the road into consideration. Cross culverts and bridges play a vital role in draining water across the road. These structures should therefore be routinely maintained through activities such as de-silting, removing debris within the culverts, and replacing of damaged culverts.

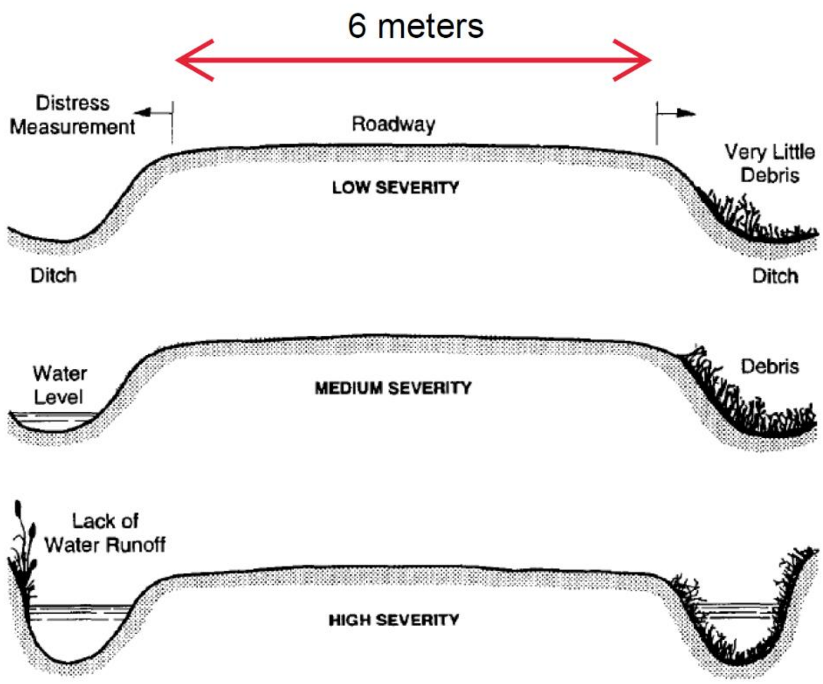


Figure 2.9: Severity levels of inadequate roadside drainage (USACE, 1995)

2.5.3 Inadequate gravel thickness

Walker (2002) states that an adequate gravel layer is required to carry and distribute traffic loads to the lower pavement layers of the road. Similarly, CSIR (2000) recommends a minimum gravel thickness of 150mm because the wearing course gradually reduces under the effects of traffic and environmental factors. The quality of the gravel material is also important and laboratory tests should be carried out to determine the gradation and durability of the gravel material before it can be used in any M&R interventions (Walker, 2002). CSIR (2000) also observes that the rate of gravel loss is a function of the material properties and traffic loading, which means that gravel loss increases significantly with an increase in traffic and material quality deterioration. It is therefore essential that regular inspections are done during which the gravel thickness is checked by physically excavating small holes in the wheel tracks to measure the gravel thickness. If found inadequate, the M&R intervention would involve importing gravel material and re-processing the wearing course CSIR (2000).

2.5.4 Surface deformation

The surface deformation of unpaved roads due to traffic and environmental factors includes distresses such as corrugations (washboarding), potholes and ruts (Walker, 2002). In contrast, CSIR (2000) suggests that corrugations, potholes, erosion gullies and ruts are a result of deficiencies in material properties and has developed a rating scale for the degree of each observed distress.

Corrugations are described by USACE (1995) as closely spaced waves (ridges and valleys) observed at regular intervals across an unpaved road and are caused by traffic and loose aggregate. Alzubaidi (1999) argues that corrugations are formed as a result of the gravel becoming sandy due to gradually wearing under traffic and dislodgement of loose aggregate. Cudworth and Rahman (2023) add that corrugations significantly reduce the ride comfort on unpaved roads causing vehicles to have poor directional stability. This distress is mostly observed at sections where there is frequent vehicular acceleration, deceleration, and cornering. According to Walker (2002), moderate corrugations are treated by light grading with a motor grader while severe corrugations require scarification and re-processing of the wearing course and in some extreme cases importation of additional gravel material during re-processing may be required.

Potholes are a menace to users of unpaved roads and are described as bowl-shaped depressions on the road surface that expand rapidly under traffic (USACE, 1995). According to Cudworth and Rahman (2023), potholes can cause significant damage to vehicles if allowed to expand and lead to the development of roughness on unpaved roads. Potholes develop when the wearing course material is worn away leaving a depression which when filled with water, dissolves the finer particles, and are splashed out when vehicle tires impact the potholes (Alzubaidi, 1999). Walker (2002) suggests that isolated potholes can be manually filled by hand during routine maintenance, however, severe occurrence of potholes requires re-processing of the spot sections manifesting this distress.

Rutting is also a common distress on unpaved roads described as surface depressions along the vehicle wheel path parallel to the centerline of the road (USACE, 1995). The cause of this defect is either by repeated vehicle passes (traffic abrasion) or by deformation of the subgrade as shown in Figure 2.10.

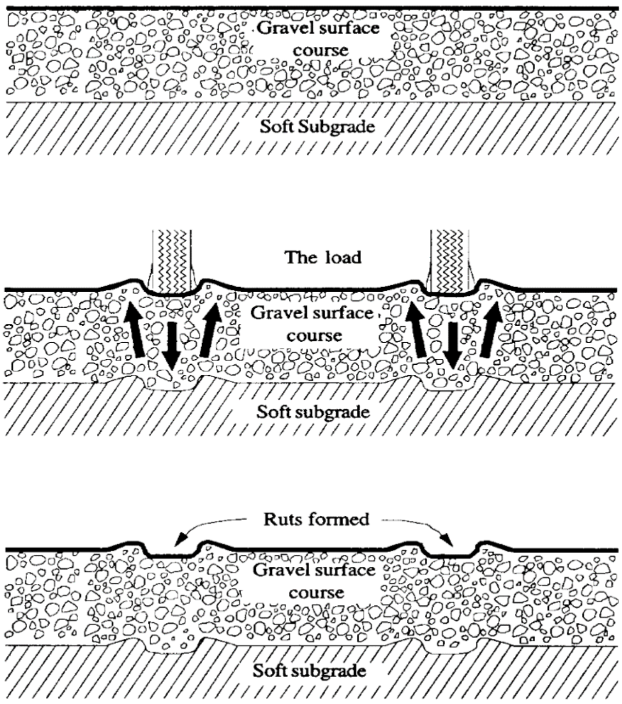


Figure 2.10: Rutting due to subgrade deformation (Alzubaidi, 1999)

Ruts are very destructive to an unpaved road because they create channels that prevent surface water runoff from getting into the side drains. The water instead moves along these newly formed channels creating gullies that expose the road subgrade layers (CSIR, 2000). Walker (2002) recommends that the M&R interventions for rutting in the wearing course as medium grading to return the displaced gravel into the wheel paths. He however adds that occurrence of rutting attributed to subgrade deformation requires a complete reconstruction of the road layers.

Erosion gullies are also a common distress on unpaved roads especially in tropical climates and are described as loss of surfacing material due to the action of water flow on the road surface (CSIR, 2000). CSIR (2000) further argues that the road surfacing material's ability to resist erosion depends on that material's shear strength. In contrast, Wang et al. (2021) assert that there are several impacting factors associated with erosion gullies on unpaved roads, however, most notably are gradient, side drainage area, material properties and climatic precipitation. They add that of these factors, the road gradient and side drainage area have the greatest influence on the extent and severity of erosion gullies.

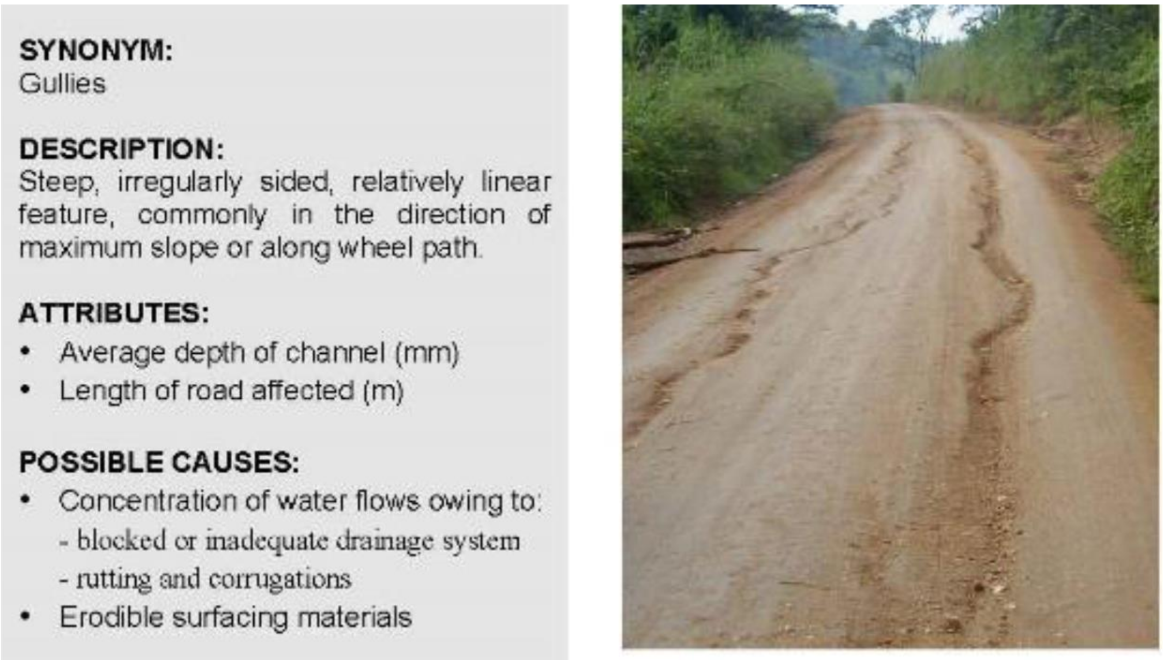


Figure 2.11: Longitudinal erosion gullies (Alzubaidi, 1999)

Erosion gullies can occur transversely or longitudinally on the road surface (as shown in Figure 2.11) and lead to dangerous driving conditions due to the increased roughness brought on by the deep erosion channels (CSIR, 2000). Mwaipungu and Allopi (2016) mention that because gravel material is removed from the unpaved road surface and deposited into the side drainage, the wearing course material properties change significantly leading to increased deterioration of the road surface. They add that erosion gullies can be measured according to their depth and length of road affected using a straight edge and wedge.

2.5.5 Dust

Dust is a common occurrence on unpaved roads generated when vehicle tires dislodge the silt-sized particles (2–75 μm) in the gravel wearing course (Cudworth and Rahman, 2023; Alzubaidi, 1999). Dust is a distress that can lead to air pollution and decreased visibility on unpaved roads with frequent traffic. CSIR (2000) proposes that the dust distress is measured according to only two ratings i.e., acceptable or unacceptable. In contrast, USACE (1995) measures the severity of dust generated as low, medium, and high. Low severity implies that the normal traffic produces thin dust that does not obstruct visibility while high severity applies to normal traffic generating a thick dust cloud that obstructs visibility causing traffic to slow down. CSIR (2000) suggests that this distress can be minimised by applying a dust palliative, however, this in practice is expensive and treatment of dust is normally not done. As such, Walker (2002) suggests that the lost fines can be reclaimed from the road shoulder and re-processed into the wearing course during the restoration of the road camber.

2.5.6 Loose gravel

CSIR (2000) states that loose gravel is formed by the revelling action of the wearing course under traffic loading. Similarly, Brooks et al. (2011) assert that loose gravel accumulates on the surface of unpaved roads due to heavy traffic and poor material properties forming berms of loose segregated material. They add that these berms can measure between 150mm to 600mm in width running longitudinally along the direction of traffic and are concentrated between the wheel paths and shoulders of unpaved roads. Loose gravel is a problematic distress because the dislodged stones may damage vehicles or windscreens and are a safety hazard to both motorists and pedestrians. CSIR (2000) suggests that this distress can be measured based on the thickness of the berm. Likewise, Brooks et al. (2011) propose that measurement of these berms is done by scrapping off the loose gravel with a pickaxe leaving a path for taking depth measurements of the berm. This distress can be remedied by carrying out routine grading and processing of the loose gravel on the unpaved road surface.

2.5.7 Stoniness

Stoniness is a common occurrence on unpaved roads and is defined by Brooks et al. (2011) as a measure of the oversize stones embedded on the road surface after the fines have been removed by traffic action and climatic precipitation. The maximum particle size for the gravel wearing course material should be 37.5mm and this must be controlled during gravelling operations at the construction stage (CSIR, 2000; Cudworth and Rahman, 2023). Stoniness leads to rough riding quality, grading difficulties during maintenance activities, flacky or sharp stones that can cause damage to vehicle tires and the development of corrugations (CSIR, 2000). Assessment of this distress can be done visually while travelling at an average vehicle speed of 40km/hr. The degree of this distress is recorded on a 1 to 5 severity scale basing on the impact of the embedded stones on the riding quality of the unpaved road (CSIR, 2000).

2.5.8 Relationship of distresses with functional and structural performance for unpaved roads

The functional performance of unpaved roads can be assessed by the condition assessment methods described in section 2.7. These methods are carried out by observing the road surface conditions, the distresses found, and their respective degree of severity (Filho et al., 2024). Structural performance on the other hand is assessed based on the load capacity of the pavement structure and its dimensioning. Similarly, Jones and Paige-Green (2015) state that functional performance for unpaved roads focuses on aspects like ride quality, dust levels, and overall usability while structural performance relates to the road's ability to maintain its shape and integrity under traffic and environmental factors. They add that the functional and structural performance for unpaved roads are often intertwined. For example, corrugations directly affect ride quality (functional) and also accelerate surface material loss (structural). A comparison relating distress types with functional and structural performances is summarised in Table 2.4.

In contrast, Filho et al. (2024) argue that only distresses related to the formation of potholes and wheel tracks are structural while all other distresses observed on unpaved roads are classified as purely functional. This research study has therefore only focused on the functional performance of unpaved roads.

Table 2.4: Summary table relating distress type with functional and structural performances

Distress Type	Functional Performance Impact	Structural Performance Impact
Camber loss	• Reduced ride quality • Increased risk of accidents	• Loss of shape and stability • Increased maintenance needs
Inadequate drainage	• Potential for hydroplaning • Steering difficulties • Reduced traction	• Loss of fines • Increased risk for further deterioration
Inadequate gravel thickness	• Reduced stability	• Loss of surface material • Reduced structural integrity
Corrugations	• Reduced ride quality • Increased vehicle operating costs • Increased risk of accidents	• Loss of surface material • Increased surface roughness • Increased risk of further corrugation
Potholes	• Significant ride quality issues • Potential for vehicle damage • Increased risk of accidents • Reduced traction	• Localised structural failure • Loss of surface material • Reduced structural integrity • Potential for further deterioration
Rutting	• Reduced traction • Increased risk of accidents	• Permanent deformation of gravel layers • Reduced drainage capacity
Erosion gullies	• Potential for road closure • Safety hazard	• Reduced structural integrity • Increased risk of further erosion • Reduced drainage capacity
Dust	• Reduced visibility • Health concerns for road users and nearby communities • Increased environmental impact	• Loss of surface material • Loss of fines • Reduced surface strength

Distress Type	Functional Performance Impact	Structural Performance Impact
	• Increased risk of accidents	
Loose gravel	• Reduced traction • Increased risk of accidents • Skidding hazard • Potential for vehicle damage	• Loss of surface material • Reduced load-bearing capacity
Stoniness	• Reduced ride quality • Reduced traction • Potential for vehicle damage	• Increased surface roughness • Reduced structural integrity

2.6 Causes of deterioration on unpaved roads

Alzubaidi and Magnusson (2002) define deterioration as the gradual worsening of the road condition due to the combined action of traffic and environment on the wearing course of an unpaved road. This definition is supported by Pearson (2011) who states that, since the surface material on an unpaved road serves as both the wearing course and base course of the road pavement, then the deterioration is governed largely by the surface material's behavior to traffic loads and environmental factors. In contrast, Oduola (2003) asserts that the deterioration process on unpaved roads varies from country to country and largely depends on the type and quality of material used as the wearing course. He adds that procedures employed, and material compaction achieved during the construction process are key factors that affect the deterioration of unpaved roads.

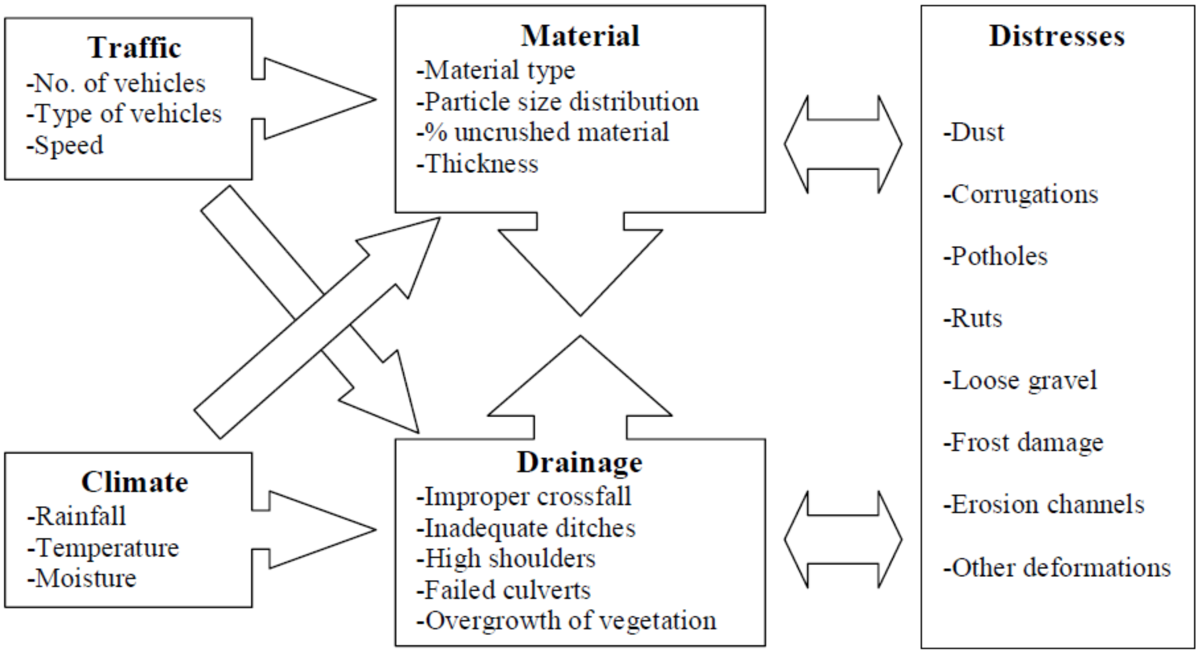


Figure 2.12: The deterioration process on gravel roads (Alzubaidi & Magnusson, 2002)

Alzubaidi and Magnusson (2002) developed a schematic representation of the deterioration process (as illustrated in Figure 2.12) that identifies four key impacting factors of deterioration on gravel roads. It is important to note that the distresses discussed in section 2.5 are a result of the deterioration process. These factors are; traffic considerations, climatic conditions, material properties and drainage considerations (Alzubaidi and Magnusson, 2002). Each of these factors are discussed in detail in the succeeding passages.

2.6.1 Traffic considerations

According to Alzubaidi and Magnusson (2002), traffic considerations are a major cause of deterioration in gravel roads because maintenance costs increase as the traffic volumes, axle loading and traffic speeds increase. Simply put, the larger the traffic, the greater the scope of the maintenance activities required to keep a gravel road at optimal service levels. In contrast, MoWT (2010) argues that the mechanism of deterioration on gravel roads is mainly related to the traffic volume (number of vehicles per day) than the axle loads (weight of the vehicles). MoWT (2010) adds that the traffic volume should be used in the design of gravel road pavements as opposed to cumulative standard axle loads. This view is contrary to Alzubaidi and Magnusson

(2002), who state that subjecting a gravel road to heavy traffic such as timber trucks increases the rate of deterioration much faster than having a high traffic volume. All in all, it should be noted that the traffic volume or heavy traffic loads can have a devastating effect on the deterioration of gravel roads.

2.6.2 Climatic conditions

Climatic conditions are another key impacting factor of deterioration on gravel roads. These conditions include rainfall, humidity, and temperature variations (Alzubaidi and Magnusson, 2002). According to Muhwezi et al. (2021) gravel roads in Uganda require re-gravelling interventions of 1-2 years after construction owing to the heavy rains as the leading cause of increased rates of deterioration. Heavy rains erode the surface of a gravel road forming erosion gullies, wash away the fine aggregate particles, weaken the road subgrade through water ingress and make the road generally sensitive to the action of traffic (Alzubaidi and Magnusson, 2002).

Humidity and temperature variations are also menacing to gravel roads because high temperatures accelerate the drying of the wearing course material which leads to the creation of excessive dust (Alzubaidi and Magnusson, 2002). It is therefore accurate to conclude that heavy rains combined high temperatures accelerate the deterioration of gravel roads leading to the formation of most distresses observed on gravel roads.

2.6.3 Material properties

The material properties of the surface wearing course are also a major cause of deterioration in gravel roads. The material properties including the particle size distribution, particle shape, and petrographic composition are key features of the strength of the gravel wearing course and the ability of the surface aggregate material to withstand the crushing action of traffic (Alzubaidi and Magnusson, 2002). In Uganda, suitable wearing course material for gravel roads are determined by the Grading Coefficient (GC) and Shrinkage Product (SP) which are both determined from the sieve analysis tests carried out on the natural gravel material found at various borrow pits (MoWT, 2010). Being that the Shrinkage Product (SP) value is obtained from the Linear Shrinkage and the percentage pass through the 0.425 mm sieve, it is important to obtain material with SP values not exceeding 400 to avoid a very dusty wearing course material (MoWT, 2010). Additionally, the SP is used to evaluate the potential for shrinkage and settlement of the aggregate material during and after construction of the gravel wearing course. Ultimately, the GC and SP are important parameters in the design and construction of unpaved roads. They influence the road's cross-sectional geometry, stability, drainage, ride quality and thickness of the aggregate layers. The GC and SP are invaluable in selecting appropriate aggregate materials, designing the road cross section, camber (slope), and determining construction and maintenance requirements for unpaved roads (Jones and Paige-Green, 2015).

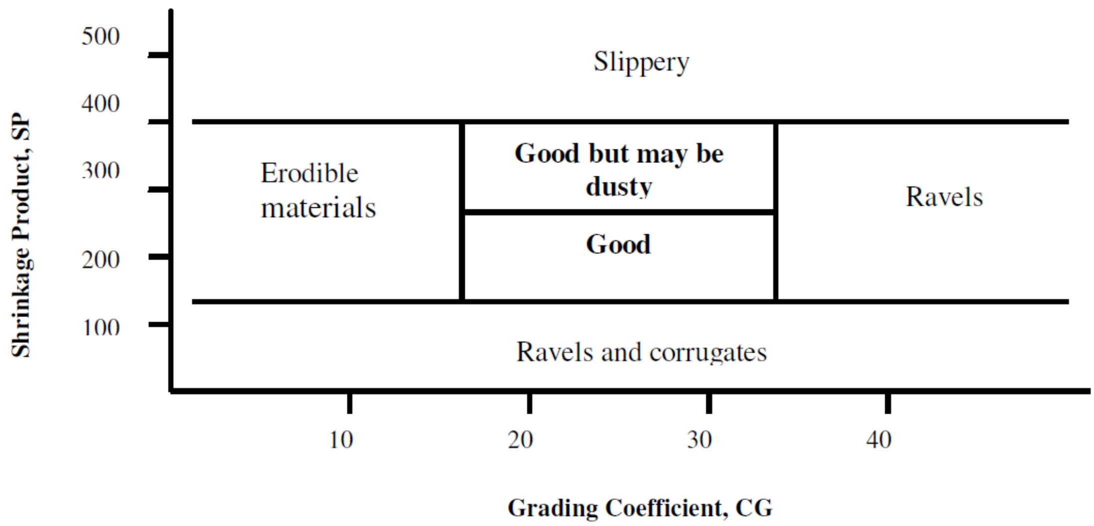


Figure 2.13: Expected Performance of Gravel Wearing Course Material (MoWT, 2010)

In Uganda, the material found naturally existing at the various borrow pits intended for use as gravel wearing course material usually fails to meet the requirements of “Good” indicated in Figure 2.13. This is because the sources of “Good” gravel are dwindling and currently the haulage distances are up to 80km which makes the use of “Good” gravel uneconomical for road agencies (MoWT, 2010). This means that agencies are forced to make do with the material readily available within the road vicinity irrespective of the fact that when used, the rate of deterioration experienced will be much greater.

2.6.4 Drainage considerations

According to Alzubaidi and Magnusson (2002) the drainage considerations are directly related to the geometric aspects of the gravel road. These aspects i.e., road camber (crossfall), vertical alignment (grade), and road width affect the adequacy of surface and rainwater drainage of gravel roads. They add that roads in winding and hilly terrain need more frequent maintenance to slow the deterioration process. This is due to the fact that rainwater flows much faster over the surface and in the side drainage system due to the steep gradients leading to the formation of erosion gullies, potholes and corrugations. Overgrown vegetation in the side drains also leads to increased deterioration of the gravel roads because the side ditches are unable to adequately drain the water away from the pavement (Pearson, 2011). In summary, the drainage considerations i.e., improper crossfall, inadequate ditches, high shoulders, failed culverts, and overgrowth of vegetation increase the rate of deterioration of gravel roads. Table 2.5 summaries the distresses discussed in Section 2.5 and the deterioration factors discussed in Section 2.6 and remedy actions associated with these distresses.

Table 2.5: A summary of distresses, deterioration factors and remedy actions.

Distress	**Causes of distress / Deterioration factors**	**Remedy mechanisms**
Camber loss	• Traffic action • Heavy rains combined with high temperatures	Re-grading and re-gravelling
Inadequate drainage	• Geometric considerations • Inadequate side drainage maintenance	Regular side drain maintenance
Inadequate gravel thickness	• Traffic action • Heavy rains combined with high temperatures	Re-gravelling using imported gravel material
Corrugations	• Aggregate is gradually broken down by traffic and sand is formed • Heavy rains • Poor material properties	Re-grading and re-gravelling
Potholes	• Poor road shape and drainage • Poor grader operation practice • Enlargement of corrugation troughs	Re-grading and re-gravelling

Distress	Causes of distress / Deterioration factors	Remedy mechanisms
	• Material and moisture variability	
Rutting	• Deformation of the subgrade under traffic action • Poor material properties	Routine blading
Erosion gullies	• Flow of water over the road • Poor shear strength of material	Increasing the shear strength of the wearing course material and re-grading
Dust	• Traffic speed • Dry climatic conditions	Apply dust palliatives to bind the dust particles
Loose gravel	• Deficiency of fine material • Poor particle size distribution • Inadequate compaction	Blend fine material with gravel to increase cohesion
Stoniness	• Poor particle distribution of gravel material • Poor compaction of areas adjacent to stones	Blending of material to achieve required shrinkage product

2.7 State-of-the-Practice of unpaved road condition assessments

In a global context, unpaved road condition assessment methods differ from country to country, however, categorization of these methods is generally grouped into manual and automated assessments (Huntington and Ksaibati, 2011). The following section will review the popular unpaved road condition assessments used by road agencies.

2.7.1 Manual condition assessments

Manual condition assessments are subdivided into visual *"windshield"* evaluations and measured condition surveys (Saeed et al., 2020; Aleadelat and Wright, 2018; Huntington and Ksaibati, 2011). The Gravel PASER method is a visual windshield survey that is widely used in the U.S. by local agencies and evaluates gravel road conditions from the decision makers point of view (Aleadelat and Wright, 2018). The Gravel PASER being a simplified method that rates the road condition on a scale of 1

(Failed) to 5 (Excellent), assesses three major distresses i.e., camber, drainage, and gravel thickness (Walker, 2002). Additionally, Walker (2002) asserts that other distresses like potholes, corrugations, rutting, and dust are secondary and should not influence the primary evaluation of the road condition. This assessment is carried out by a rater or assessor travelling in a vehicle at an average speed of 40km/hr guided by the Gravel PASER manual that includes example photographs and verbal descriptions of the distresses for the various ratings (Huntington and Ksaibati, 2015).

Brooks et al. (2011) on the other hand suggest that the Gravel PASER manual allows assessors to rate an unpaved road based on the type, extent, and severity of observed distresses. They add that being a visual assessment, Gravel PASER is a subjective rating that heavily relies on the assessor’s ability to estimate the severity and extent of distresses rather than focusing on physical distress measurements. Because of this, researchers Huntington and Ksaibati (2015) assessed the Ride Quality Rating Guide (RQRG) and the Gravel Roads Rating System (GRRS) developed by the Wyoming Technology Transfer Centre (WYT2/LTAP) against the Gravel PASER system. The RQRG and GRRS differ from the Gravel PASER because they assess unpaved roads on a rating scale of 1 (Failed) to 10 (Excellent) and combine the use of photographs to illustrate seven identified distresses. The research findings indicated that by increasing the rating scale from 5 (Gravel PASER) to 10 (RQRG), the error level of repeatability by multiple evaluators was decreased leading to a more accurate rating of the unpaved road condition.

In South Africa, the Standard Visual Assessment Manual for Unsealed Roads (TMH12) developed by Council for Scientific and Industrial Research (CSIR) is used by road agencies to classify road sections into one of five categories i.e., 1 (Very Good), 2 (Good), 3 (Fair), 4 (Poor), 5 (Failed) (CSIR, 2000). According to Brooks et al. (2011), TMH12 visually assesses distresses like potholes, corrugations, rutting, erosion, stoniness, dust, drainage, gravel profile and riding quality based on their severity or degree numbered 0 (distress not present) to 5 (high level of distress). Huntington and Ksaibati (2015) argue that the South African TMH12 system requires considerably more effort and training of the assessors than the U.S. Gravel PASER. Another key difference highlighted by the researchers is the difference in the smoothness expectation between South African and U.S. unpaved roads. They contend that although both systems have a similar 5-point rating scale, the cutoff between fair and poor condition assessments is 60km/hr for TMH12 and 40km/hr for Gravel PASER. This difference in smoothness expectations is down to the considerably drier climate in South Africa as compared to the U.S and as such the unpaved roads in South Africa carry higher traffic volumes (Huntington and Ksaibati, 2015).

Sweden assesses unpaved road conditions using the *Bedömning av grusväglag (Gravel road assessment)* developed by the Swedish National Road and Transport Research Institute (VTI) (Saeed et al., 2020). This assessment is only suitable for agencies with nomadic climates and assessors are encouraged to carryout condition assessments every after 3 months to collect condition data on potholes, ruts, roughness, loose gravel, and dust (Saeed et al., 2020). In addition, Saeed et al. (2020) suggests that this assessment method is to some extent similar to Gravel PASER because it subjectively measures distresses based on photographs with written descriptions indicating the various levels of severity. In contrast, Alzubaidi (1999) argues that the Swedish gravel road assessment method objectively measures roughness using various equipment like the PCA road meter , GM profilometer, and CHLOE profilometer. The method classifies the unpaved road condition based on a 3-point rating scale i.e., Class 1 (good), Class 2 (acceptable), and Class 3 (poor) (Saeed et al., 2020).

The Unsurfaced Road Condition Index (URCI) is another popular measured condition assessment developed by the U.S. Army Corps of Engineers (USACE) for unpaved roads (Huntington and Ksaibati, 2015). According to USACE (1995), the URCI is determined after field survey measurements of seven distresses i.e., Improper cross section, Inadequate roadside drainage, Corrugations, Dust, Potholes, Ruts and Loose aggregate. Similarly, Huntington and Ksaibati (2015) mention that each of the observed distresses are measured either linearly or by area and rated according to a 3-point severity level of low, medium or high. They add that deduct values are obtained for each measured distress and these values are then used to determine the overall URCI according to a 0 (Failed) to 100 (Excellent) scale.

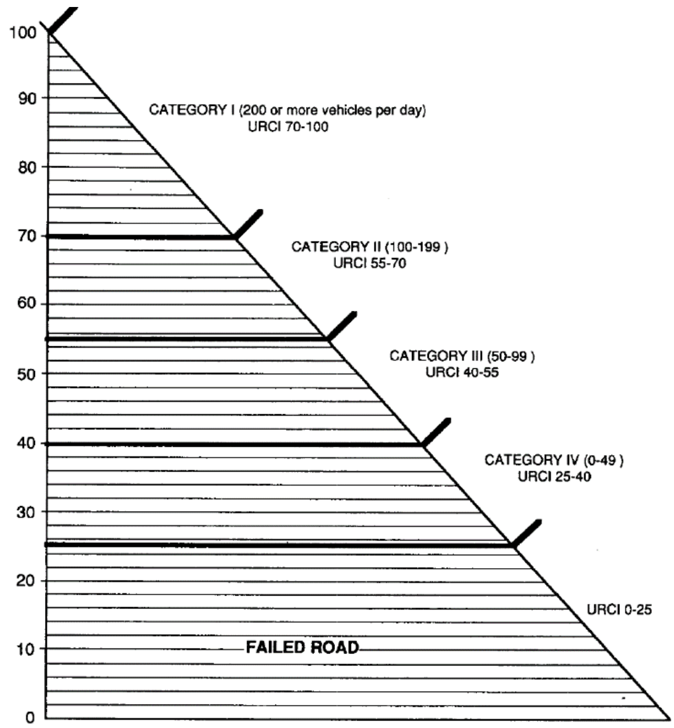


Figure 2.14: Maintenance priority graph (USACE,1995)

Saeed et al. (2020) state that being one of the earliest attempts by agencies to develop a consistent and quantifiable condition assessment method for unpaved roads means that URCI should be popular, however, this does not seem to be the case due to being rigorous and slow as compared to the Gravel PASER. One of the key distinctions of URCI is that it classifies unpaved roads according to traffic volume, construction history and road rank. This means that the M&R strategies are based on a combination of the overall URCI and the daily traffic volume as shown in Figure 2.14 (Saeed et al., 2020). Sampling of field measurements is made by dividing the unpaved road into segments that measure up to 325 square meters and required every kilometre. The measurement of observed distresses in each segment is rigorous and time consuming because each of the seven distresses must be quantified and recorded (Saeed et al., 2020). A summary of the advantages and disadvantages of each manual condition assessment method discussed in section 2.7.1 is provided in Table 2.6.

Table 2.6: A summary of the advantages and disadvantages of each manual condition assessment method

Manual Condition assessment method	Advantages	Disadvantages
Gravel PASER	• Simple method that rates road condition on a 5-point rating scale of 1 (Failed) to 5 (Excellent). • Quick visual windshield survey. • Assesses three major distresses i.e., camber, drainage, and gravel thickness.	• Subjective rating. • Heavily relies on assessor’s experience in distress identification.
Standard Visual Assessment Manual for Unsealed Roads (TMH12)	• Visual assessment with 5-point rating scale of 1 (Very Good) to 5 (Failed). • Assesses distresses like potholes, corrugations, rutting, erosion, stoniness, dust, drainage, gravel profile and riding quality based on their severity.	• Requires considerably more effort and training of the assessors.
Ride Quality Rating Guide (RQRG)	• Visual method that assesses unpaved roads on a rating scale of 1 (Failed) to 10 (Excellent). • Combines the use of photographs to illustrate seven identified distresses. • Reduced error level of repeatability.	• Subjective rating.
Unsurfaced Road Condition Index (URCI)	• Field survey measurements of seven distresses i.e., Improper cross section, Inadequate roadside drainage, Corrugations, Dust, Potholes, Ruts and Loose aggregate. • Observed distresses are rated according to a 3-point severity level of low, medium, or high.	• Rigorous and time consuming because each of the seven distresses must be quantified and recorded for every kilometre.

Manual Condition assessment method	Advantages	Disadvantages
	• Classifies unpaved roads according to traffic volume, construction history and road rank.	
Bedömning av grusväglag (Gravel road assessment)	• Pavement condition rated according to a 3-point rating scale i.e., Class 1 (good) to Class 3 (poor). • Condition assessments carried out every after 3 months. • Collects condition data on potholes, ruts, roughness, loose gravel, and dust. • Objectively measures roughness.	• Only suitable for agencies with nomadic climates.

2.7.2 Automated condition assessments

According to Shtayat et al. (2020) manual condition assessments are subjective, lack repeatability and are time consuming. They add that automated condition assessments use data collection equipment like Unmanned Aerial Vehicles (UAVs), Smartphone applications, Satellite imagery, DashCams and sophisticated survey vehicles thus quickly providing objective data because they eliminate human errors during data collection. On the other hand, Kans et al. (2020) disagree by stating that automated condition assessments are not preferable to manual assessments for unpaved roads because they require special vehicles and/or equipment that is expensive and could easily be damaged by dust or water commonly associated with gravel roads.

Aleadelat and Wright (2018) also suggest that automated surveys are still impractical for local agencies. They argue that because the condition of unpaved roads rapidly changes, assessments are required quarterly. This high frequency of data collection makes automated surveys very expensive for local agencies with limited budgets. It could be argued whilst debate exists on which type of assessment has advantages over the other, automated condition assessments are slowly being adopted by agencies for their unpaved road networks.

Research into the use of Unmanned Aerial Vehicles (UAVs) was carried out by Zhang (2012) who developed a system that included a low-cost model helicopter mounted with a camera, GPS, geomagnetic sensor and Inertial Navigation System (INS). The images captured by the camera were used to generate 3-D models of the road surface thereby capturing distresses such as corrugations, potholes, and ruts to a ground resolution of up to 5mm. This UAV-based digital imaging system enables agencies collect data using unpiloted airborne equipment that enables distress measurements to be made in office using computer-aided techniques. Additionally, Zhang (2012) suggests that using this system eliminates the need to carryout manual field measurements thus ensuring that condition assessments are carried out rapidly, safely, and efficiently.

According to Aleadelat and Wright (2018), smartphones have in recent times also been used in assessing the condition of unpaved roads particularly in determining the roughness by estimating the International Roughness Index (IRI). Their research revealed that the accelerometer within a smartphone can be used to record the vertical vibrations while driving over an unpaved road thereby providing feedback on the riding quality of the road surface. Similarly, Saeed et al. (2020) assert that a number of smartphone based applications like RoadLab, Roadroid, RoadBounce and RoadSense have been developed for measuring road roughness. These applications measure IRI by correlating the vibrations in the smartphone accelerometer and positioning them using the GPS built within the smartphone.

The use of accelerometers to collect roughness data for unpaved roads has also been deployed by the Forest Engineering Research Institute of Canada (FERIC) through the Opti-Grade system (Brooks et al., 2011). This system took advantage of the large number of logging haul trucks using the Canadian unpaved road network by enabling agencies install accelerometers and GPS units into these trucks. In so doing, the agencies can collect roughness data while the trucks are in service on their normal routes thereby reducing on costs associated with field data collection (Brooks et al., 2011).

Saeed et al. (2020) however add that accelerometer-based devices are still inefficient because they are only limited to measuring roughness and are unable to identify the nature of the road surface distresses. Similarly, Kans et al. (2020) mention that smartphones are unable to capture the actual surface topology meaning that distresses such as ruts, camber or gravel loss are not identified by the applications. Another downside to using smartphone applications is the continued occurrence of false positives in the data attributed to sudden barking, gear changes, or abrupt movements of the passengers in the vehicle during condition assessments (Saeed et al., 2020).

Sophisticated survey vehicles mounted with laser scanners, road profilers, cameras, GPS and accelerometers can also be used to evaluate unpaved roads (Radopoulou and Brilakis, 2016). These vehicles are expensive to purchase and have high operation and maintenance costs which makes their regular use on unpaved road condition assessments uneconomical (Radopoulou and Brilakis, 2016). That said, Tanyu and Waters (2015) argue that condition survey vehicles are very effective when it comes to collecting condition data on paved roads because the on board laser scanners can identify and measure surface defects while driving at high speeds. Limited research has been undertaken in the use of survey vehicles on unpaved roads because distresses such as dust and loose gravel makes the use of these vehicles uneconomical due to high maintenance costs.

2.8 Status of Pavement Management in Uganda

In Uganda, roads carry about 95% of the freight traffic and 99% of the passenger traffic with a 6% annual growth rate in the volume of traffic on the road network (World Bank, 2020). The 159,461 km road network in Uganda consists of 21,105 km of National Road and 138,356 km of DUCAR (District, Urban, Community and Access Roads) (NPA,2020). Several agencies known as Designated Agencies (DA's) are tasked with managing this extensive road network (UNRA, 2022; World Bank, 2020; NPA, 2020).

The Uganda National Roads Authority (UNRA) is the DA responsible for developing and maintaining the 21,105 km of National Roads and as of August 2022, 5,879 km (28%) of National Roads were paved while 15,227 km (72%) were unpaved (UNRA, 2022). It should also be noted that these National Roads carry around 80% of the total traffic, however, they constitute only 13% of the total road network in the country (World Bank, 2020). 38,603 km of District Roads are managed by District Local Governments of which only 107 km (0.28%) are paved and 38,496 km (99.72%) unpaved. Urban and Municipal Councils manage the 19,959 km of Urban Roads of which 1,230 km (6.2%) are paved and 18,729 km (93.8%) unpaved. The Community and Access Roads are managed by a lower tier of Local Government (LC III) and these 79,794 km are unpaved consisting of both gravel and earth roads. Overall, only 7,216 km (5%) of the total road network is paved and 152,246 km (95%) is unpaved (MoWT, 2021). Table 2.7 summaries the total paved and unpaved road network in Uganda illustrated in Figure 2.15 (UNRA, 2022).

Table 2.7: Summary of Ugandan paved and unpaved road network

Road classification	**Length (km)**			**Percentage**	
	Paved	**Unpaved**	**Total**	**Paved**	**Unpaved**
National Roads	5,879	15,227	21,105	28%	72%
DUCAR	1,337	137,019	138,356	1%	99%
Total	**7,216**	**152,246**	**159,461**	**5%**	**95%**

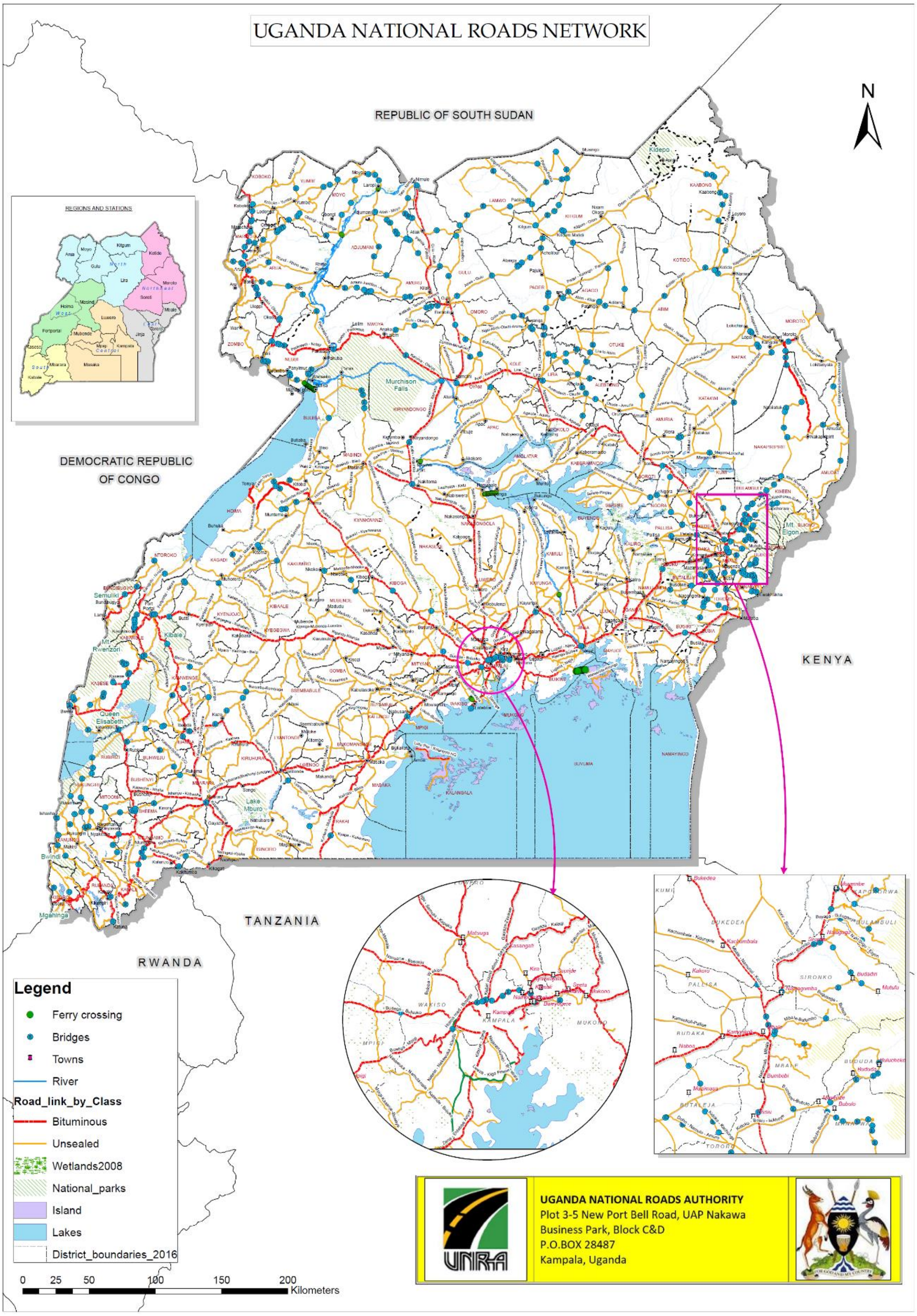


Figure 2.15: Ugandan National Road Network (UNRA, 2022)

2.8.1 Funding for road maintenance in Uganda

The Uganda Road Fund (URF) is the government organization responsible for funding road maintenance activities nationally (URF, 2022). Prior to URF's establishment in 2008, the government disbursed road maintenance funds from the treasury directly to the agencies. This approach was however, inefficient as it led to an accumulation of a maintenance backlog of 3,500 km, an equivalent to 33% of the 11,000 km national road network at the time i.e. between 1998 to 2008 (MoWT, 2021). Within this 10-year period, the road condition for DUCAR in poor to very poor condition also increased from 30% to 55%. The establishment of a road fund (URF) was therefore to address the inadequate funding levels of road maintenance by providing an institutional mechanism through which revenues from road user charges could be put at the disposal of DA's without being subjected to the bureaucratic procedures associated with the Consolidated Government Fund (MoWT, 2021). This has however, still not been achieved because of legal impediments constraining the independent collection of revenues from road user charges by URF. This implies that at the moment, road maintenance funding is released quarterly from the Consolidated Government Fund and is not fully responsive to the road condition and road network needs to adequately assess and mitigate the road maintenance backlog growth (URF, 2022; MoWT, 2021).

Obunguta and Matsushima (2020) argue that because Uganda adopted a time dependent management policy instead of a condition dependent policy for managing pavements, this implies that the chronic growth of the road maintenance backlog will persist until road maintenance funding is linked to road usage and condition. The available funds for road maintenance have increased from Uganda Shillings (UGX) 273 billion ($74 million) in Financial Year (FY) 2010/11 to UGX 427 billion ($116 million) in FY 2020/21 (URF, 2022). Though funding has increased over the years, the total maintenance needs have increased at a faster rate than the increment in available funding. For example, FY 2020/21 indicated available maintenance funding of UGX 427 billion ($116 million) against a total requirement estimated at UGX 1.939 trillion ($526 million). The available funding met only 23.9% of the needs leaving 76.1% i.e., UGX 1.512 trillion ($410 million) of the maintenance needs unmet (MoWT, 2021). This massive shortfall in maintenance funding implied that periodic maintenance activities are unfunded thereby leading to a deterioration in the condition of the road network.

URF must therefore persuade government to increase funding for road maintenance so as to protect the existing road asset and also mitigate the maintenance backlog build-up.

2.8.2 Pavement condition assessments for unpaved roads in Uganda

The Uganda National Roads Authority (UNRA) maintains 15,227 km of unpaved roads representing 72% of the National Road network through its Stations located in all regions of the Country (UNRA, 2022). The Directorate of Road Maintenance in UNRA maintains unpaved roads through the 23 Stations spread across the Central, Eastern, Northern, South-western, Western and North-eastern regions of Uganda using force-account and works contractors (UNRA, 2022). Each of these Stations has a minimum of two (02) road maintenance engineers tasked with carrying out regular pavement condition assessments for the unpaved road network within their jurisdiction. The engineers carryout visual surface condition surveys following the UNRA manual on visual condition assessments for unpaved roads.

The UNRA visual inspections manual (2017) describes nine (09) distresses namely, (1) Gravel Thickness, (2) Roughness, (3) Potholes, (4) Rutting, (5) Corrugations, (6) Erosion Gullies, (7) Drainage Condition, (8) Drainage Formation Level and (9) Material Quality. Each of these unpaved road distresses is assessed according to a 5-point severity scale. For example, the Roughness severity scale illustrated in Table 2.8 indicates Grade 1 for a smooth comfortable ride where the International Roughness Index (IRI) value is less than 5. Grade 5 on the other hand is used to indicate an impassable road state with an IRI value of greater than 16 (UNRA, 2017).

Table 2.8: Roughness severity scale for unpaved National Roads (UNRA, 2017)

Grade	Description
1	Ride very smooth and very comfortable; No/slight unevenness of the profile; No rutting or potholes; IRI value <5.
2	Ride smooth/fair and comfortable; Moderate unevenness of the profile; Moderate rutting but no potholes; IRI value >=5 and <7.
3	Ride poor and uncomfortable; Frequent unevenness of the profile Significant rutting, corrugations and occasional potholes; Moderate speed reduction; IRI value >=7 and <9.
4	Ride very poor and very uncomfortable; Severe unevenness of the profile; Extensive rutting, corrugations and several potholes; Driving speed much lower than speed limit; Road unsafe owing severe unevenness; IRI value >=9 and <16.
5	Impassable except by 4 Wheel Drive vehicles. IRI value >=16.

Reporting on the condition of the National unpaved road network is based on the Visual Condition Index (VCI) which rates the road condition on a scale of Very Good (100) to Very Poor (0) as shown in Table 2.9. The UNRA VCI rating is calculated for every 1 km section of unpaved road from the combination of the weighting factor of each distress and the severity of the individual distress (UNRA, 2017).

Table 2.9: VCI rating scale for unpaved National Roads (UNRA, 2017)

VCI rating	VCI range
Very Good	86% to 100%
Good	71% to 85%
Fair	51% to 70%
Poor	31% to 50%
Very Poor	0% to 30%

Table 2.10: Condition for unpaved National Roads in Uganda (UNRA, 2022)

Unpaved Roads Condition (km)					Unpaved Roads Condition (%)		
FY	**Good**	**Fair**	**Poor**	**Total**	**Good**	**Fair**	**Poor**
2017/18	3,678	9,755	2,558	15,993	23%	61%	16%
2018/19	3,802	8,079	3,960	15,841	24%	51%	25%
2019/20	3,945	4,215	2,426	10,586	37%	40%	23%
2020/21	4,930	5,552	2,345	12,827	38%	43%	18%
2021/22	2,223	8,961	1,445	12,629	18%	71%	11%

The Ministry of Works and Transport (MoWT) sets performance objectives for UNRA regarding the condition of unpaved roads. For FY 2021/22 the *"% of National roads in fair to good condition"* was to be kept above 70% for unpaved roads. Consequently, UNRA achieved this target as indicated in Table 2.10 and had 89% of the unpaved National roads in fair to good condition (UNRA, 2022). It should also be noted that although the UNRA VCI is a 5-point rating scale i.e., Very Good, Good, Fair, Poor and Very Poor, UNRA reports the unpaved road condition using a 3-point scale i.e., Good, Fair, Poor.

The DUCAR network on the other hand, consists of 137,019 km of unpaved roads making up 99% of the DUCAR network. This massive unpaved road network is maintained by 121 District Local Governments, 41 Municipal Councils, 1,155 sub-counties and 214 town councils as sub-agencies of the respective District Local Governments (URF, 2022). Visual condition assessments on these unpaved roads are carried out by District, Municipal and Town Council Engineers basing on the MoWT Road Maintenance Management Manual (2010).

The MoWT manual (2010) describes five (05) condition categories i.e. (5) Excellent, (4) Good, (3) Fair, (2) Poor, (1) Very Poor and identifies five (05) distresses which include Roughness, Rutting, Loss of Camber, Potholes and Edge step. The severity and extent of each distress is measured using a 4-point grading for severity and a 5-point grading for the extent to determine the condition rating on a scale of 5 (Excellent) to 1 (Very Poor). It should however be noted that most DUCAR agencies do not carry out the unpaved road condition assessments in accordance with the MoWT manual because of complexity of use, lack of training and inadequate resources.

2.8.3 The need for an improved condition assessment method for unpaved roads

Thus, it is clear from section 2.8, that there is an inherent need for an improved condition assessment method for unpaved roads that will effectively and efficiently determine the condition of the unpaved road network in Uganda to address the limited assessment resources and colossal backlog in condition assessment, hence the purpose of this research study. The need for a GRCI (Gravel Road Condition Index) stems from the fact that DUCAR agencies are failing to use the MoWT manual 5-point rating scale due to its complexity of use, lack of training and inadequate resources. In practice, District, Municipal and Town Council Engineers are determining the condition rating only through assessor's experience and without application of any subjective and objective condition assessment methodologies.

Secondly, the GRCI can be used to predict deterioration, and as such would be a planning tool for triggering the maintenance and rehabilitation (M&R) needs for the unpaved road network. Consequently, the M&R needs can be quantified and costed so as to improve the budgeting processes associated with maintaining the unpaved road network.

2.9 Summary of Chapter

This literature review has discussed pavement management systems and their structures and pavement condition assessments for both paved and unpaved roads. The review also critically assessed the distresses associated with unpaved roads before reviewing the current state-of-practice for manual and automated condition assessments of unpaved roads. Crucially, a review of the status of pavement management in Uganda exposed the need for an improved condition assessment method for the unpaved DUCAR network and introduced the Gravel Road Condition Index (GRCI) that establishes an efficient and effective method for assessing the condition of unpaved roads. The next chapter will review existing literature regarding prediction models for pavement deterioration that have been developed for unpaved roads with particular emphasis on the gravel loss prediction models.

Chapter Three

PREDICTION MODELS FOR PAVEMENT DETERIORATION

3.1 Introduction to prediction models

According to Haas, Hudson and Falls (2015), deterioration or performance prediction models are essential in establishing the lifecycle costs of a road pavement. Additionally, AASHTO (2012) states that performance predication models are vital tools for predicting future conditions of the pavement, and to identify the timing of the maintenance and rehabilitation activities required to keep the road at good serviceability levels. It is important to note however, that while paved roads typically have a service life of approximately 20 years, unpaved roads have a much shorter service life spanning several months to a few years (Ksaibati and Saha, 2017). This shorter service life is because unpaved roads deteriorate faster than paved roads due to factors like traffic loads, material quality and precipitation (Ksaibati and Saha, 2017). This deterioration over time can be predicted and modeled using deterministic or probabilistic techniques (Chamorro and Tighe, 2011).

Haas, Hudson and Zaniewski (1994) illustrated how deterioration predication models could be applied in estimating the needs year when rehabilitation interventions will be required to return the road pavement to acceptable service levels (See Figure 3.1).

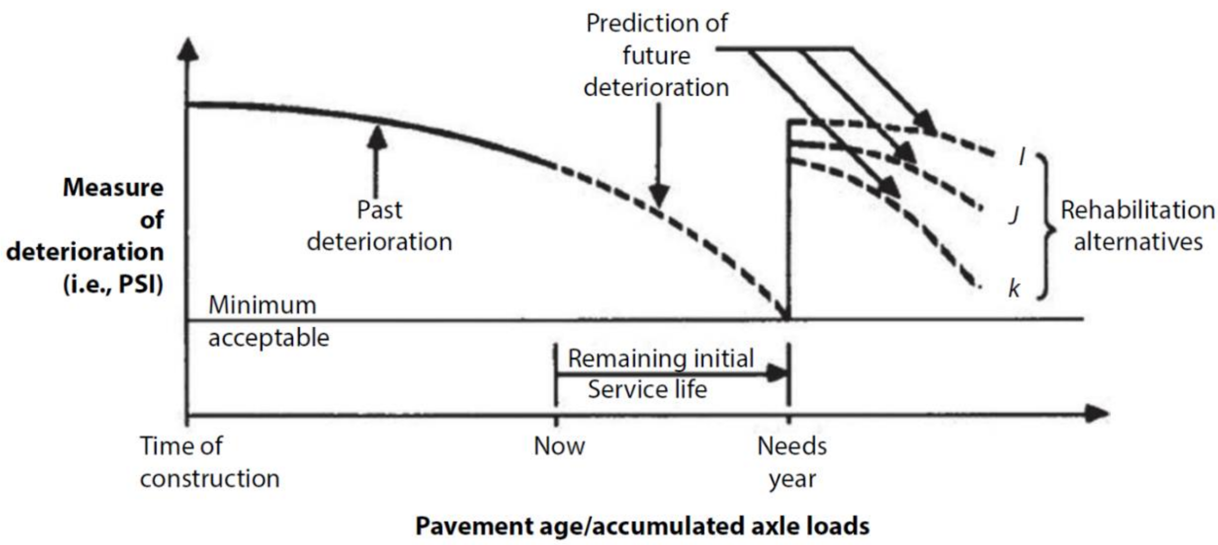


Figure 3.1: Deterioration model illustrating future pavement deterioration and rehabilitation alternatives (Haas, Hudson and Zaniewski, 1994)

This chapter will, therefore, discuss performance prediction modelling techniques and critique the commonly used performance prediction models for unpaved roads. This chapter will also review the prediction models used in various geological and geographical regions including the prediction models applied to the Ugandan context.

3.2 Performance prediction modelling techniques

There are two basic types of performance predication models found in literature namely: deterministic or probabilistic (Garcia, 2000; Chamorro and Tighe, 2011). With deterministic models, the pavement condition is predicted as a precise value based on measured or observed deterioration. On the other hand, probabilistic models predict the condition of a pavement by assigning probabilities of occurrence to a range of possible pavement conditions (Garcia, 2000). Both these performance predication models are reviewed in-depth in the following sub-sections.

3.2.1 Deterministic performance models

Deterministic performance models assume pavement deterioration follows a predetermined pattern, allowing an equation to link pavement condition to one or more casual variables (Oladele, 2013). Abaza (2004) argues that these models use mathematical equations derived from measured or observed deterioration, employing mechanistic, empirical, and mechanistic-empirical methods. It should be noted however, that deterministic models are best suited for agencies with historical pavement data and enough survey data to identify statistically significant deterioration trends (Pérez-Acebo et al., 2020). Regression analysis establishes relationships between dependent and independent variables, using techniques like least squares to determine the best statistical fit. Cudworth and Rahman (2023) contend that most deterministic models are developed empirically through regression analysis or mechanistic-empirical correlations. The three types namely: empirical, mechanistic, and mechanistic-empirical are further discussed in the following sub-sections.

3.2.1.1 Empirical Models

Oladele (2013) asserts that empirical models are used by road agencies with extensive pavement data, employing statistical techniques like regression to develop casual relationships between variables. These models require long-term condition databases and depend on independent variables to predict pavement performance (Garcia, 2000). However, empirical models have limitations because extrapolating from the available condition data increases the uncertainty of the predicted pavement performance outside the available data set (Prozzi et al., 2017). Accuracy of these models can be assessed through regression and statistical tests.

Examples of empirical models include the California Department of Transportation's PaveM, which comprises of 180 empirical models linked to three individual distresses i.e., IRI, cracking and rutting with pavement age as the only variable (Shu et al., 2021). Another example of a deterministic empirical model relevant to this study is the gravel loss prediction model developed by Mwaipungu and Allopi (2016) for the Iringa region in Tanzania. This gravel loss prediction model based on the population average approach to establish a functional relationship between gravel loss (the dependent variable) and the independent variables (i.e., traffic volume, soil characteristics and climate).

3.2.1.2 Mechanistic Models

According to Prozzi et al. (2017), mechanistic models are developed using observations and laboratory testing. They add that physical principles and observations are used to describe the causal effects of variables, allowing for more general applicability. These models depict the performance of the pavement under the combined actions of traffic loading and environmental factors (Oladele, 2013). However, mechanistic models have limitations in that they require detailed structural information, depend on complex analyses, and are not well-suited for condition data focused on surface distresses (Mubaraki, 2010). Examples of mechanistic models include a mechanistic roughness model developed by Saleh et al. (2000) in Florida (USA) relating IRI to asphalt thickness, axle load, and load repetitions. This study will however not make use of such a mechanistic model because the application of finite element structural analysis and elastic layer theory on unpaved roads is impractical due to the short service life associated with unpaved roads.

3.2.1.3 Mechanistic-Empirical Models

Mechanistic-empirical models combine mechanistic and empirical approaches. They first test and measure pavement performance under traffic and environmental factors, then use these results to predict future performance (Mubaraki, 2010). According to Prozzi et al. (2017), mechanistic models predict stresses and strains, while empirical models use the results from the mechanistic models to predict the pavement performance. This approach leverages the strengths of both empirical and mechanistic models, though at an increased level of complexity.

Oladele (2013) mentions that mechanistic-empirical models are based on theoretical postulations calibrated using regression analysis of observed data. However, they require considerable efforts during data acquisition because they are complex and technically intensive (Oladele, 2013). Major mechanistic-empirical models, like those in the Mechanistic-Empirical Pavement Design Guide, were developed using US road test data and are not transferable to unpaved roads in Uganda due to varying climatic and environmental factors, therefore, these models are not applicable to this study.

3.2.2 Probabilistic performance models

Probabilistic performance models predict the likelihood of future pavement conditions based solely on the current state, without relying on historical data (Garcia, 2000). These models address the subjectivity of field observations by treating the pavement condition as a random variable capable of incorporating the uncertain factors associated with pavement deterioration (Oladele, 2013). Markov chain, Bayesian, and Artificial Neural Network (ANN) probabilistic models are commonly used and have attracted the greatest interest from researchers as discussed in the succeeding sub-sections. It is however important to note that probabilistic models have one major advantage over deterministic models which is that; probabilistic models require much less data and as such are more suited to road agencies with limited historic and field observed information (Mahmood et al., 2016; Pérez-Acebo et al., 2020).

3.2.2.1 Markovian Models

Markov Chain models are popular probabilistic models used for pavement performance prediction since the 1980s (Wang, 2016 cited Golabi et al., 1982). These models assume the future pavement condition depends only on the current state and independent of the past pavement condition (Wang, 2016). Markov Chain models transform condition ratings into discrete states and use a Transition Probability Matrix to predict future deterioration (Oladele, 2013). The matrix can be determined from expert experience and survival curves thus requiring less data than deterministic models. This implies that Markov Chain models are suitable for both network and project level pavement prediction (Wang, 2016).

These models follow homogeneous or non-homogenous approaches (Zheng Li, 2005). Non-homogenous models can integrate deterioration rates and maintenance interventions into the transition matrix, while homogenous models assume constant variables during analysis (Zheng Li, 2005). Markov Chain models are advantageous in predicting deterioration from current condition and measuring performance risks, though they cannot accurately model the complex pavement deterioration process. For example, Abaza (2016) developed a simplified staged-homogenous Markov model that predicts the future pavement distress condition rating for paved roads in Palestine. Such a model, however, is not applicable to this study because the Markov model requires annual condition data for each year (assuming 10 condition states) and this historical data is currently unavailable in any of the road agencies in Uganda.

3.2.2.2 Bayesian Models

According to Pérez-Acebo et al. (2020), Bayesian models combine expert data and field observations to predict pavement performance. While Bayesian models typically apply both subjective and objective data to predict pavement performance, these models can use only subjective data to predict future deterioration (AASHTO, 2012). Bayesian models consider parameters as random variables, allowing them to overcome poor-quality data by incorporating expert opinions (Wang, 2016). This implies that Bayesian models are advantageous because they provide a mechanism to override the influence of poor-quality data by incorporating expert opinions during modelling. This is evidenced by the research findings of George (2000), indicating that the inclusion of expert opinions in the Bayesian model generated superior models for the Mississippi Department of Transportation (MDOT) pavement management system. Bayesian models are, however, not applicable to this study due to the unavailability of reliable field observed condition data for unpaved roads in Uganda that is essential in carrying out Bayesian regression analysis.

3.2.2.3 Artificial Neural Network (ANN) Models

Artificial Neural Network models have become popular for pavement deterioration prediction due to their ability to process complex, nonlinear data and detect interactions between variables (Pérez-Acebo et al., 2020). ANN models can solve pavement distress prediction problems that are difficult for other models to reslove. They work by repeatedly processing test data and adjusting weights to improve performance, without requiring causal relationships (Tukaram Thube, 2012). ANN models can also optimize maintenance strategies (Hosseini et al., 2020). The major advantage of using ANN models is their ability to model large, complex, nonlinear data and detect all possible interactions between predictor variables which cannot be done by other models (Hosseini et al., 2020: Yao et al., 2019). However, ANN models require large amounts of data, which may not be available to road agencies with limited budgets, making them inappropriate for this study.

Table 3.1: Summary comparison between performance predication models for paved roads

Type of performance model		Advantages	Disadvantages
Deterministic performance models			
1	Empirical Models	• Accuracy of models can be assessed through regression and statistical tests	• Require long-term condition databases
2	Mechanistic Models	• Apply both physical principles and observations to describe the causal effects of variables, allowing for more general applicability	• Require detailed structural information • Depend on complex analyses • They are not well-suited for condition data focused on surface distresses

Type of performance model		Advantages	Disadvantages
3	Mechanistic-Empirical Models	• Use the strengths of both mechanistic and empirical approaches	• Require considerable efforts during data acquisition • They are complex and technically intensive
Probabilistic performance models			
4	Markovian Models	• Can predict deterioration from the most current condition rating without relying on the use of average regression curves • Able to measure performance risks	• Cannot accurately model the complex pavement deterioration process
5	Bayesian Models	• Able to overcome poor-quality data by incorporating expert opinions • Can use only subjective data to predict future deterioration	• Require reliable field observed condition data
6	Artificial Neural Network (ANN) Models	• Able to model large, complex, nonlinear data and detect all possible interactions between predictor variables • Can optimize maintenance strategies	• Require large amounts of data

3.3 Performance prediction models for unpaved roads

Research studies into the development of performance prediction models for unpaved roads were first carried out by the Overseas Unit of the Transport and Road Research Laboratory (TRRL), in conjunction with the Kenyan government in the early 1970's (T. E. Jones, 1984). These TRRL studies developed performance prediction models for gravel loss, rut depth, depth of loose surface material and roughness. The gravel loss model of the TRRL studies included traffic loading, rainfall, road alignment, material properties and maintenance periods as input parameters to the mathematical equation (Jones, 1984).

The TRRL studies were followed by the Brazil-UNDP-World Bank road cost study from 1976 to 1981 that involved a wider range of material types, traffic volumes, and road geometries for unpaved roads (Paterson, 1987). Paterson (1987) added that the results from the Brazil study led to the development of the widely used Highway Design and Maintenance (HDM) performance prediction models. The HDM models for gravel loss and roughness are suitable for economic analysis at network level to evaluate the optimum maintenance interventions and are applicable to widely differing climates and wearing course materials (Paterson, 1987). In contrast, Aleadelat et. al (2019) argues that the World Bank HDM models require lengthy inputs such as terrain type, traffic, crashes, fatalities, speed, and geometric data that supersedes the capabilities of small road agencies. This means that the World Bank HDM models are not user friendly for road agencies with small budgets and limited staff expertise.

The South African unpaved road deterioration models developed between 1983 and 1989 differed considerably from the World Bank models due to their simplicity and containing fewer variables (Paige-Green, 1995). The South African models exposed the fact that the World Bank models were not effectively transferable to the climate and material properties of South Africa and Namibia (Paige-Green, 1995). Simply put, each climatic and geological region requires bespoke performance prediction models that are specific to each geographical location. The following subsections will therefore review the most popular gravel loss, roughness, and shape loss models applicable to different geographical locations.

It is important to note that of the three categories of unpaved road prediction models (i.e., gravel loss, roughness, and shape loss) gravel loss is arguably the most important prediction parameter (Van Wijk et al., 2019).

3.3.1 Review of Gravel Loss prediction models

Gravel Loss (GL) is the amount of gravel wearing course material that has been eroded and requires replacement to restore the original designed thickness of the gravel wearing course (Prashant et al., 2018 cited Gichaga and Parker, 1988). Prashant et al. (2018) add that gravel loss is measured in average millimeters reduction of the original gravel layer thickness with the nominal thickness of the gravel wearing course varying between 150 to 250 mm depending on the roadbed strength characteristics. Mwaipungu (2015), on the other hand, defines gravel loss as a time-dependent reduction in the thickness of the gravel wearing course through mechanical displacement of the gravel materials to the surrounding area. The rate of gravel loss is dependent on the intensity and duration of rainfall, traffic loading, and wind forces. Other factors affecting the rate of gravel loss are surface cross-fall, road width, geometric alignment, material quality, construction methods, level of material compaction, and the maintenance practices (Mwaipungu, 2015: Prashant et al., 2018).

According to Henning et al. (2008), determining the extent of gravel loss is important for road agencies so as; *(1)* to estimate the future re-gravelling quantities required for the road network, *(2)* to prioritize allocation of limited gravel resources, *(3)* to assist road asset managers in programming and cost allocation and *(4)* to evaluate alternative gravel surfacing materials and maintenance practices. That notwithstanding, gravel loss prediction models are arguably the most important prediction tools for estimating the re-gravelling future needs because they reliably predict gravel material performance (Mwaipungu, 2015). Figure 3.2 illustrates the timely prediction of when gravel roads will need to be re-gravelled once the minimum thickness has been attained. This prediction is important for budgeting purposes and to obtain an economically defendable re-gravelling cycle that can be used trigger maintenance activities (Mwaipungu, 2015).

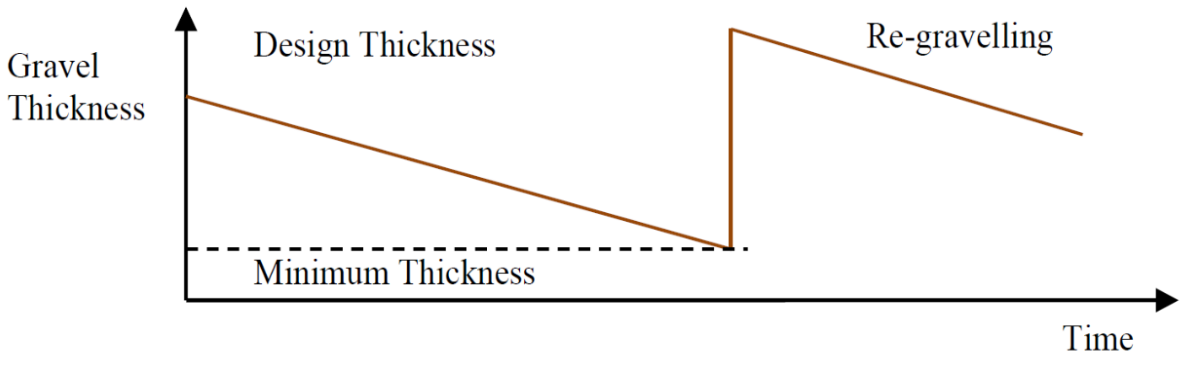


Figure 3.2: Trend of gravel loss for unpaved roads under maintenance (Paterson, 1987)

Since the results of gravel loss predication models rely on a number of environmental and mechanical factors, it is important to review the gravel loss prediction models relevant to this study namely:

- Kenyan (TRRL) gravel loss prediction model
- Brazilian gravel loss prediction model
- HDM-4 gravel loss prediction model
- South African (TRH 20) gravel loss prediction model
- Australian (ARRB) gravel loss prediction model
- Ugandan gravel loss prediction model

Table 3.2 below summaries the variables linked to each of the six (06) gravel loss prediction models stated above. It should be noted that the variables in each of the reviewed models vary significantly based on individual researcher's assumptions regarding the climatic, traffic volume and soil properties of the gravel roads within the researcher's geographical location. For example, the Kenyan (TRRL) model takes into consideration the traffic volume, rainfall, soil properties and road geometry while the Ugandan model only considers traffic volume, rainfall and soil properties excluding road geometry and maintenance frequencies. This researcher will therefore review these six (06) gravels loss models with the aim of identifying the key variables pertaining to gravel loss models. This researcher has also noted that all the six (06) gravel loss prediction models reviewed in the succeeding subsections are deterministic-empirical models developed by mathematical and statical relationships whose accuracy can be established through regression analysis and statistical accuracy tests. Secondly, this researcher further notes that none of the six (06) gravel loss prediction models link the condition of the pavement with the annual predicted gravel loss.

Table 3.2: Variables linked to gravel loss prediction models (Mwaipungu, 2015)

S/N	**Variables**	**Models**					
		Kenyan	**Brazilian**	**HDM-4**	**TRH20**	**ARRB**	**Ugandan**
1	**Traffic Volume**						
1.1	Annual average daily traffic (AADT)	√		√			

S/N	Variables	Models					
		Kenyan	Brazilian	HDM-4	TRH20	ARRB	Ugandan
1.2	Average daily traffic (ADT)		√		√	√	√
2	**Precipitation (rainfall)**						
2.1	Mean monthly precipitation (MMP)		√	√		√	√
2.2	Weinert N-value				√		
2.3	Annual rainfall (m)	√					
3	**Material properties**						
3.1	Material type (f)	√					
3.2	Plasticity Index (PI)			√		√	
3.3	Passing 0.075 mm sieve (P075)			√	√	√	√
3.4	Passing 26.0 mm sieve (P26)				√		
3.5	Plastic Limit (PL)				√		
4	**Road Geometry**						
4.1	Average rise and fall (m/km) /Road Width	√		√			
4.2	Gradient (%) for uniform road length		√	√			
4.3	Average curvature (degrees/km)			√			
5	**Calibration factors**						
5.1	Kgl / Kkt			√			
6	**Maintenance**						
6.1	Number of days since last blading		√			√	

3.3.1.1 Kenyan (TRRL) gravel loss prediction model

The 1970's Kenyan (TRRL) study developed the first gravel loss prediction model that was a multivariate equation relating the annual gravel loss at a point in time to annual traffic, annual rainfall, percentage gradient, and material constants for the different types of gravel materials used as the wearing course in Kenya (Mwaipungu, 2015: Jones, 1984). The study was a collaboration between the Transport and Road Research Laboratory (TRRL-UK) and the Kenyan government. During this study, the rate of gravel loss was recorded as the vertical loss in millimeters of the eroded road surface material. Additionally, measurements were made at three monthly intervals and recorded by using optical survey techniques (i.e., dumpy levels). Each experimental section was divided at 5 meter intervals along a 60 meter length and profiles taken at 250mm increments across the road prism. On each side of a test section, concrete mark stones were installed parallel to the center of the road and 300mm square plates were placed outside the road prism to monitor the movement between the road structure and the concrete benchmarks (Jones, 1984).

The Kenyan (TRRL) gravel loss prediction model was developed on the premise that gravel loss from the wearing course eventually leads to permanent damage of the road structure unless remedial treatments are undertaken (Jones, 1984). Jones (1984) further stated that the general equation for this governing principle was borrowed from the agricultural sector represented by the following Equation (3.1).

Soil loss = Soil erodibility x Ground slope factor x Rainfall factor ***(eq. 3.1)***

From eq. 1, the Kenyan (TRRL) study developed the gravel loss prediction model as shown in Equation (3.2).

$$\mathbf{GLA = f\,(TA^2 / (TA^2 + 50))\,(4.2 + 0.092TA + 3.50RL^2 + 1.88VC)} \qquad \textit{(eq.3.2)}$$

Where, f = 1.29 for lateritic gravel
1.51 for quartzitic gravels
0.96 for volcanic gravels
1.38 for sandstone gravels

GLA = annual gravel loss in mm
TA = annual traffic volume in both directions measured in 1000 of vehicles
RL = Annual rainfall in metres
VC = rise and fall (gradient) in %

3.3.1.2 Brazilian gravel loss prediction model

The 1980’s Brazilian gravel loss prediction model was developed after extensive data collection funded by the World Bank was undertaken in Brazil. The model predicted gravel loss as a function of monthly rainfall, gradient, and traffic volume over a specific time period (Paterson, 1987). The Brazilian gravel loss model was used in economic analysis and evaluated the relationships between different maintenance interventions with the appropriate construction methods (Paterson, 1987). The Brazilian gravel loss prediction model was derived as shown in Equation (3.3). It is important to note that the Brazilian model could be used as a universal model that incorporated traffic, gradient, and rainfall effects but however excluded material properties (Paterson, 1987).

$$\mathbf{GL = 10^{-5}\,[30 + 180(MMP) + 72(MMP)(G)]\,(h)(ADT)(T)} \qquad \textbf{\textit{(eq.3.3)}}$$

Where,	GL	= average gravel loss (mm)
	MMP	= mean monthly precipitation (m/month)
	G	= average absolute gradient (%)
	ADT	= annual average daily traffic (vpd)
	h	= proportion of heavy vehicles in traffic (fraction)
	T	= time period (days)

3.3.1.3 HDM-4 gravel loss prediction model

The results from the Kenyan and Brazilian studies discussed in the preceding subsections were used to develop the Highway Design and Maintenance (HDM-3) gravel loss prediction model which has now been updated to the HDM-4 model (Van Wijk et al., 2019). The HDM-4 model predicts the annual gravel loss as a function of traffic, monthly rainfall, gradient, horizontal alignment, and material properties of the gravel wearing course (Van Wijk et al., 2019).

Mwaipungu (2015) argues that since the HDM-4 gravel loss prediction model transforms average monthly rainfall into average annual rainfall, no specific distinction can be made between uniform and seasonal climates. He further adds that another drawback of the HDM-4 gravel loss prediction model is that geometric elements of the road such as the width of traffic lanes, camber and superelevation are not included in the model. Additionally, other factors like the compaction of the wearing course, and the effect of maintenance practices are not considered by the model (Mwaipungu, 2015).

The HDM-4 gravel loss prediction model is represented by the following Equation (3.4)(Uys, 2011).

$$MLA = Kgl * 3.65 (3.46 + 2.46 * MMP * RF * 10^{-4} + KT * AADT) \qquad \textit{(eq.3.4)}$$

Where, MLA = predicted annual material loss (mm/year)

RF = average rise and fall of the road (m/km)

MMP = mean monthly precipitation (mm/month)

AADT = annual average daily traffic (vehicles/day)

KT = traffic-induced material whip-off coefficient

Kgl = gravel material loss calibration factor

Uys (2011) adds that the traffic-induced material whip-off coefficient (KT) can be expressed as a function of rainfall, road geometry, and material properties as follows in Equation (3.5):

$$KT = Kkt * MAX [0, 0.022 +(0.969*C/57,300) + 3.42*MMP*P075j*10^{-6} - 9.2*MMP*PIj10^{-6} – 1.01*MMP*10^{-4}] \qquad \textit{(eq.3.5)}$$

Where, *C* = average horizontal curvature of the road (deg/km)

PI*j* = plasticity index of material *j* (*j* = *g* if a gravel road; *j* = *s* if an earth road)

P075*j* = amount of material passing a 0.075-mm sieve

Kkt = traffic-induced material loss calibration factor

MAX = maximum value obtained >0

3.3.1.4 South African (TRH 20) gravel loss prediction model

The late 1980’s study carried out in the then Transvaal Province of South Africa and Namibia investigated the performance of wearing course gravel materials with regard to their rates of deterioration under traffic and environmental factors (Paige-Green, 1989: Mwaipungu, 2015). This study led to the development of a gravel loss prediction model that has been incorporated into the Technical Recommendations for Highways (TRH) 20 manual of South Africa. The TRH 20 model predicts gravel loss as a function of traffic volume, climate, and material properties as expressed in Equation (3.6) (Paige-Green, 1989: Mwaipungu, 2015).

GL =3.65 [ADT (0.059 + 0.0027N - 0.0006P26) - 0.36N - 0.0014PF + 0.0474P26] *(eq.3.6)*

Where,	GL	= average gravel thickness loss (mm)
	ADT	= average daily traffic in both directions
	N	= Weinert N value *(ranges from 1 in wet areas to more than 10 in arid areas and incorporates annual rainfall)*
	P26	= percentage of gravel materials passing 26.5mm sieve
	PF	= product of plastic limit and percentage passing 0.075mm sieve

From the results of the South African study Paige-Green (1989) suggested that this model should replace the Kenyan and Brazilian models because the TRH 20 model predicted gravel loss with a higher accuracy (i.e., within 11mm for predicted verses actual gravel loss). Another advantage is that the TRH 20 model does not incorporate road geometry and maintenance practices making it simpler to use than other models (Paige-Green, 1989: Mwaipungu, 2015).

3.3.1.5 Australian (ARRB) gravel loss prediction model

Between 2002 and 2011, the Australian Road Research Board (ARRB) conducted a local roads deterioration study across different parts of Australia (Kadar and Martin, 2014: ARRB, 2020). The data collected from the various test sites was used to develop the ARRB model that predicted gravel loss as a function of traffic volume, rainfall and material properties as indicated in Equation (3.7) (Kadar and Martin, 2014).

GL = D * (0.00985ADT + 0.02991MMP + 0.00583PF) ***(eq.3.7)***

Where,	GL	= average gravel thickness loss (mm) across roadway
	D	= time period in hundreds of days (days/100)
	ADT	= average daily vehicular traffic in both directions, in vehicle/day
	MMP	= mean monthly precipitation, in mm/month
	PF	= Plasticity factor (PI × P075)
	P075	= amount of material passing the 0.075 mm sieve

The similarities between the ARRB model and the South African (TRH 20) model cannot be overlooked as both models do not incorporate a function of road geometry. It is important to note that the ARRB model was developed from the TRH 20 model but was made specific for the Australian climate and local materials resources (Kadar and Martin, 2014).

3.3.1.6 Ugandan gravel loss prediction model

Because this research study is geographically located in Uganda, it is important to review the gravel loss prediction model appropriate for the climate and material properties in Uganda. Dr. Fredrick Were-Higenyi collaborating with Transport Research Laboratory (TRL-UK) funded by the Department for International Development (DFID-UK) carried out a study between 2002 and 2006 that led to the development of the Ugandan gravel loss prediction model (MoWT, 2010: Were-Higenyi et al., 2006). The model predicts gravel loss as a function of traffic volume, precipitation, dust, and material properties as represented in Equation (3.8).

$$\mathbf{AGL = 8.4 + 0.258\,(MMP)(ADT) + 55.02\,(MMP)\,(DR)(GM)} \qquad \textit{(eq.3.8)}$$

Where,
- AGL = Annual Gravel Loss (mm/year)
- ADT = Average Daily Traffic, both directions (vehicles per day)
- MMP = Mean Monthly Precipitation (m)
- DR = Dust ratio = P0.075 / P0.425
- GM = [300-(P2.36 +P0.425 +P0.075)]/100

and where;
- P2.36 = percentage passing 2.36 mm sieve
- P0.425 = percentage passing 0.425mm sieve
- P0.075 = percentage passing 75µm sieve

Results from the study showed that precipitation was a significant contributing factor to the annual gravel loss. The Ugandan model also revealed that when all the independent variables are kept constant, the annual gravel loss would be less the 9mm (MoWT, 2010). Furthermore, an increase in traffic volume, dust ratio and grading modulus would lead to increased gravel loss and that; the influence of grading as a maintenance intervention had no significance on gravel loss prediction (MoWT, 2010).

According to Were-Higenyi et al. (2006) the main conclusions of the study were that since most parts of Uganda receive more than two annual rainfall seasons, the gravel material properties and traffic volumes had a significant impact on the rate of gravel loss. Further still, the study compared the Ugandan model with the HDM-4 model and discovered that the average gravel loss was 20% higher than the predicted values from the HDM-4 model. This research study will therefore make use of the Ugandan model to predict pavement performance of gravel roads in Uganda.

3.4 Roughness Prediction Models

According to Paige-Green (1989), the roughness of a road is an important parameter that affects the vehicle operating costs associated with that road. He adds that the roughness of a road can inform asset managers of the influences of material quality, traffic volume, and maintenance practices deployed by a road agency. The International Roughness Index (IRI) is defined as *"the accumulated suspension vertical motion divided by the distance traveled as obtained from a mathematical model of a simulated quarter-car traversing a measured profile at 80 km/h"* (Gharieb and Nishikawa, 2021). IRI is reported in meters per kilometer (m/km) or inches per mile (in./mi) with a perfectly smooth pavement surface obtaining a score of zero (0) which means that a high IRI value translates into a poor pavement condition (Sayers et al., 1986).

Roughness prediction models for unpaved roads are the most complex. The first model was developed by the Transport and Road Research Laboratory (TRRL-UK) in association with the Kenyan government in the 1970's (Paterson, 1987). The model predicted roughness progression by deploying a bivariate polynomial relating the roughness at any point in time to traffic volume for different types of gravel materials (Paterson, 1987). Following the Kenyan (TRRL) roughness prediction model, the HDM-3 (now updated to HDM-4) model was developed which revealed that the roughness progression relationship constrains roughness to a high upper limit i.e., maximum roughness (RI_{max}) (Were-Higenyi et al., 2006). Figure 3.2 illustrates the convex function in which the rate of roughness progression decreases linearly to zero at RI_{max} (Were-Higenyi et al., 2006).

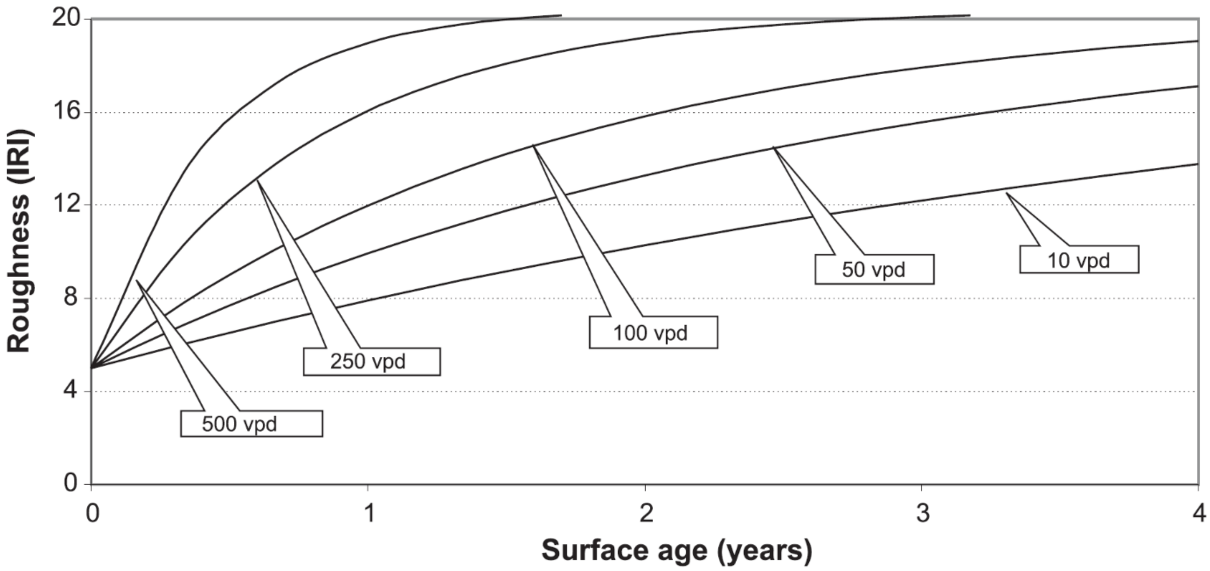


Figure 3.3: Roughness progressions on unpaved roads with no maintenance (Were-Higenyi et al., 2006).

The HDM-4 model predicts the rate of roughness progression as a function of maximum roughness, time, traffic volume and material properties as represented in Equation (3.9). Maximum roughness is expressed as a function of road geometry and material properties as represented in Equation (3.10) (Were-Higenyi et al., 2006).

$$\mathbf{RI_{TG2} = RI_{max} - b\,[RI_{max} - RI_{TG1}]} \qquad \textit{(eq.3.9)}$$

$$\mathbf{RI_{max} = max\{[21.5 - 32.4(0.5 - MGD)2 + 0.017(HC) - 0.764(RF)(MMP/1000)], 11.5\}} \qquad \textit{(eq.3.10)}$$

Where, b = exp [c (TG2 – TG1)] and $0 < b < 1$

c = -0.001 Kc [0.461 + 0.0174 (ADL) + 0.0114(ADH) - 0.0287(ADT)(MMP/1000)]

RI_{TG1} = roughness at time TG1, in m/km IRI

RI_{TG2} = roughness at time TG2, in m/km IRI

RI_{max} = maximum allowable roughness for specified material, in m/km IRI

TG1, TG2 = time elapsed since latest grading, in days

ADL = average daily light traffic (GVW < 3500kg) in both directions, in vpd

ADH = average daily heavy traffic (GVW $\geq$ 3500kg) in both directions, in vpd

ADT = average daily vehicular traffic in both directions, in vpd

MMP = mean monthly precipitation, in mm/month

HC = average horizontal curvature of the road, in deg/km

RF = average rise plus fall of the road, in m/km

MGD = material gradation dust ratio =P075/P425 if P425 > 0 and =1 if P425=0

This research study will however not make use of roughness models because these models are complex and require large amounts of data that are not readily available to Ugandan road agencies (MoWT, 2020). This is due to the fact that road agencies in Uganda only collect subjective roughness data based on visual assessments (UNRA, 2017). Additionally, IRI values are not measured by road agencies in Uganda for unpaved roads because of the lack of appropriate equipment and the enormous costs associated with the acquisition and maintenance of these equipment (MoWT, 2020). It is however important to note that the emergence of smartphone based IRI measurement applications like RoadLab, Roadroid, RoadBounce and RoadSense will make it easier and more affordable to collect IRI data in the future even for Ugandan road agencies with limited budgets. Lastly, the Ugandan gravel loss model is preferred to the HDM-4 roughness model due to its ease of use and minimal input parameters. This ease of use of the Ugandan gravel loss model over the HDM-4 roughness model is of significance to this research study since Ugandan district, municipal and town council engineers require simplified models to predict pavement performance for unpaved roads.

3.5 Shape Loss Models

Gravel loss models have long been the standard for triggering re-gravelling maintenance interventions on gravel roads, however, recently shape loss models developed in Australia and New Zealand have piqued the interest of researchers (Van Wijk, 2019). The shape loss model predicts the percentage (%) change of the road surface camber per year and can be used to determine and schedule blading maintenance interventions (Van Wijk, 2019: ARRB, 2020). The New Zealand shape loss model developed by Henning et al. (2008) was based on the illustration shown in Figure 3.3 and predicts change on the road profile shape as a function of traffic volume, blading (maintenance intervention) and material properties.

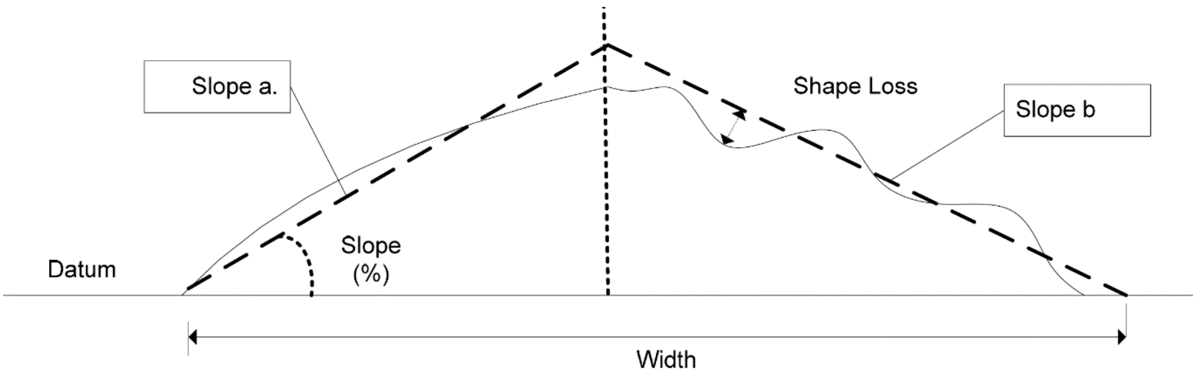


Figure 3.4: Slope and shape loss model parameters (Henning et al., 2008).

The model is represented as shown in Equation (3.11) (Henning et al., 2008).

$$dSlope = 2 * [-0.144 + ADT * (F1 - F2 * PL) + BF * (F3 * PL - F4 * ADT - F5 * CBR) + TLB * (-F6 + F7 * PI)] \quad \textit{(eq.3.11)}$$

Where, dSlope = annual change in profile

ADT = annual daily traffic

BF = number of blades

TLB = number of days since last blading

PI = plasticity index

PL = plastic limit

CBR = Californian bearing ratio

Fi = model coefficients

The Australian shape loss model on the other hand is simpler and predicts loss of shape as a function of traffic volume and material properties only as represented in Equation (3.12) (Kadar and Martin, 2014).

$$SL = F0 + F1 \times ADT + F2 \times P075 \quad \textit{(eq.3.12)}$$

Where, SL = shape loss, i.e. (%) change in pavement lane cross-fall per year

ADT = average daily vehicular traffic in both directions, in vehicle/day

P075 = amount of material passing the 0.075 mm sieve, in per cent by mass

F0, F1 & F2 = model coefficients.

Shape loss models have not been used in this study because they have not been applied in other regions with differing climatic and geological conditions from those in Australia and New Zealand. Additionally, the measurement of slopes does not adequately capture the transverse “unevenness” of the road profile caused by distresses such as rutting and corrugations (Henning et al., 2008). Furthermore, monitoring the shape (camber) loss of the road surface requires the deployment of additional manpower and survey equipment at regular periodic intervals to track the percentage change in the camber. Such activities however require additional funding which is unavailable to Ugandan road agencies with limited funding.

3.6 Summary of Chapter

The literature reviewed in this chapter revealed that although several prediction models for pavement deterioration have been developed for unpaved roads, only the deterministic-empirical gravel loss predication model can be adequately applied to varying climatic, geographical, and geological conditions. This is evidenced by the development of the Ugandan gravel loss prediction model that is comparable to the HDM-4 gravel loss prediction model.

Furthermore, the literature review in this chapter also showed that although several comprehensive gravel loss prediction models have been developed, none of them are able to link the condition of the pavement with the annual predicted gravel loss. This research has therefore attempted to establish a relationship between the novel pavement condition assessment rating developed by this researcher *(i.e., the GRCI)* and the Ugandan gravel loss prediction model for unpaved roads in Uganda. The next chapter discusses the research philosophy and methodology considered suitable for this study.

Chapter Four

RESEARCH METHODOLOGY

4.1 Introduction

Amaratunga et al. (2001) describe research methodology as a procedural framework within which a research is carried out in the built environment context. They add that it is vital for a built environment researcher to discuss and understand the adopted research philosophy and methodology before undertaking the research. Similarly, Fellows (2010) asserts that because the research philosophy and methodology are directly linked, it is imperative that both aspects are clearly understood and discussed by the researcher before proceeding to the data collection and analysis stages of the research.

Collins and Hussey (2014) suggest that it is also important to study the characteristics of the different types of research before selecting the methodology to deploy. They propose that the research is distinguished according to its purpose, process, logic and outcome, as summarised in Table 4.1. Fellows and Liu (2015) similarly classify research according to the methods to be adopted *(qualitative vs quantitative),* the purpose of the research *(exploratory, descriptive, instrumental*) and by application *(pure vs applied).* That said, the methodology adopted for research should follow a systematic, rigorous, precise, and formal process aimed at providing solutions to problems and gaining insights into new facts and relationships (Zami, 2010 cited Waltz and Bausell, 1981). This chapter will explain this process and the philosophical positions, approaches and techniques adopted in order to achieve the aims and objectives of the research.

Table 4.1: Classification of types of research (Collins and Hussey, 2014)

Type of Research	**Classification rational**
Exploratory, descriptive, analytical, predictive research	Purpose of the research
Quantitative or qualitative research	Process of the research
Pure or applied research	Outcome of the research
Deductive or inductive research	Logic of the research

This PhD research utilised the research *"onion"* model (Figure 4.1) developed by Saunders et al. (2019) to explain the philosophy, approach, methodological choice, strategies, time horizon, techniques and procedures deployed to achieve this research. This model has been adopted because of its extensive application by built environment PhD researchers and also due to its ability to provide detailed information to guide the research (Ade Bilau et al., 2018).

The following sections in this chapter will explore the existing literature regarding these six layers of the *“onion”* while also identifying the most appropriate research philosophical stance that formed the basis of the research design and methodological framework of this research.

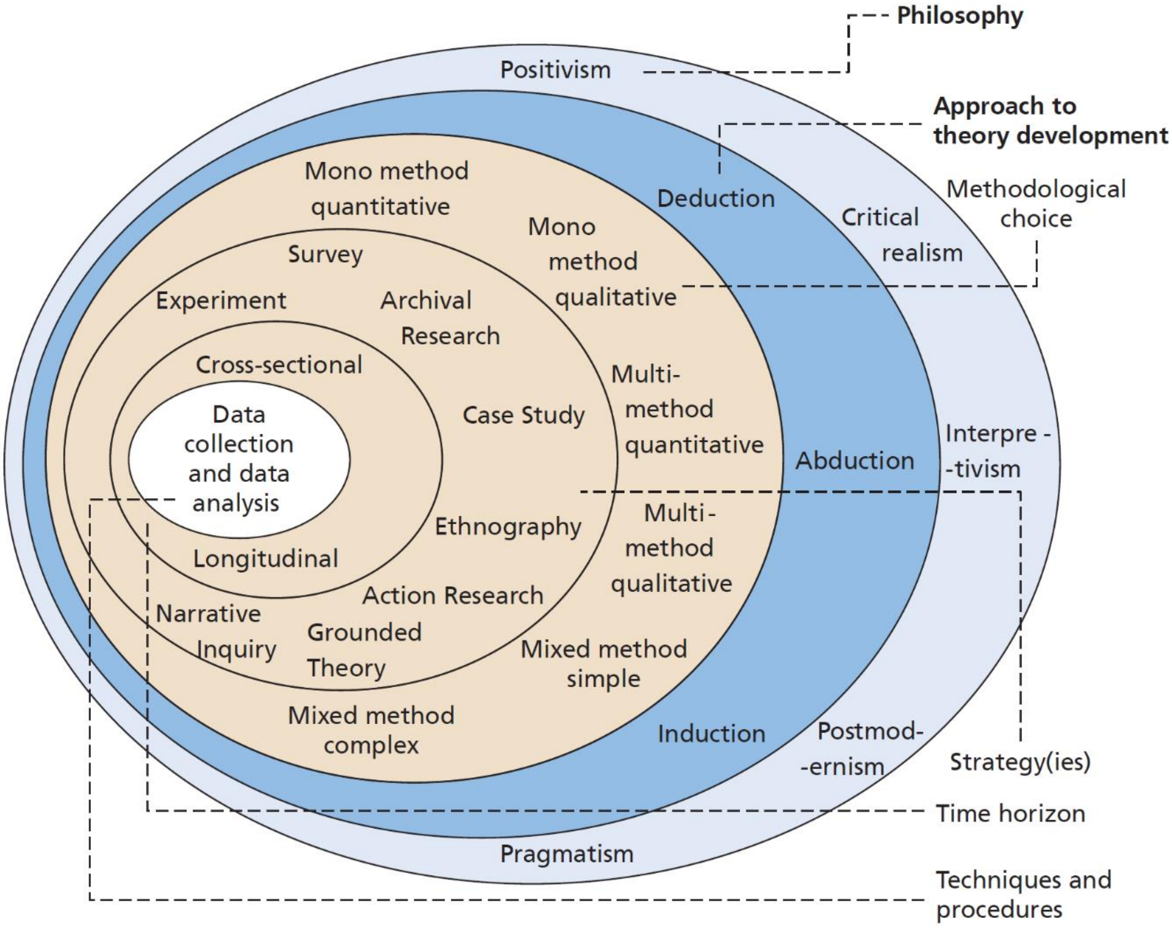


Figure 4.1: The research “onion” (Saunders et al., 2019)

4.2 Research Philosophy

Research philosophy is a set of beliefs and assumptions that shape a researcher's understanding of a study (Collins and Hussey, 2014). According to Saunders et al. (2019), the five common research philosophies in management studies are positivism, critical realism, interpretivism, postmodernism, and pragmatism, these are compared in Table 4.2. However, Easterby-Smith et al. (2002) and Agyekum-Mensah et al. (2020) argue that the main paradigms in construction engineering and management research, are positivism and interpretivism, with increased interest in pragmatism. The key philosophies of positivism, interpretivism, and pragmatism are discussed in the following sections.

Table 4.2: Comparison of five research philosophical positions (Saunders et al., 2019)

	Positivism	**Critical realism**	**Interpretivism**	**Post-modernism**	**Pragmatism**
Ontology *(nature of reality)*	Real, external, Independent, One true reality (universalism), Granular (things) Ordered.	Stratified/layered (the empirical, the actual and the real) External, independent Intransient, Objective structures, Causal mechanisms.	Complex, rich, Socially constructed through culture and language, Multiple meanings, interpretations, realities, Flux of processes, experiences, practices.	Nominal Complex, rich, Socially constructed through power relations, Some meanings, interpretations, realities are dominated and silenced by others, Flux of processes, experiences, practices	Complex, rich, external 'Reality' is the practical consequences of ideas, Flux of processes, experiences and practices
Epistemology *(what constitutes acceptable knowledge)*	Scientific method, Observable and measurable facts, Law-like generalisations, Numbers, Causal explanation and prediction as contribution.	Epistemological relativism, Knowledge historically situated and transient, Facts are social constructions, Historical causal explanation as contribution.	Theories and concepts, too simplistic, Focus on narratives, stories, perceptions and interpretations, New understandings and worldviews as contribution.	What counts as 'truth' and 'knowledge' is decided by dominant ideologies, Focus on absences, silences and oppressed/ repressed meanings, interpretations and voices, Exposure of	Practical meaning of knowledge in specific contexts, 'True' theories and knowledge are those that enable successful action, Focus on problems, practices and relevance,

	Positivism	Critical realism	Interpretivism	Post-modernism	Pragmatism
				power relations and challenge of dominant views as contribution.	Problem solving and informed future practice as contribution.
Axiology *(role of values)*	Value-free research, Researcher is detached, neutral and independent of what is researched, Researcher maintains objective stance.	Value-laden research, Researcher acknowledges bias by world views, cultural experience and upbringing, Researcher tries to minimise bias and errors, Researcher is as objective as possible.	Value-bound research, Researchers are part of what is researched, Subjective, Researcher interpretations key to contribution Researcher reflexive.	Value-constituted research, Researcher and research embedded in power relations, Some research narratives are repressed and silenced at the expense of others, Researcher radically reflexive.	Value-driven research, Research initiated and sustained by researcher's doubts and beliefs, Researcher reflexive.
Typical methods	Typically deductive, highly structured, large samples, measurement, typically quantitative methods of analysis.	Retroductive, in-depth historically situated analysis of pre-existing structures and emerging agency, Range of methods and data types to fit subject matter.	Typically inductive. Small samples, in-depth investigations, qualitative methods of analysis.	Typically deconstructive – reading texts and realities against themselves, In-depth investigations of anomalies, silences and absences, Range of data types, typically qualitative methods of analysis.	Following research problem and research question, Range of methods: mixed, multiple, qualitative, quantitative, action research, Emphasis on practical solutions and outcomes.

4.2.1 Positivism

According to Collins and Hussey (2014), positivism is underpinned by the belief that reality is independent of the researcher, whose goal should be the discovery of theories using observation and experiments i.e., empirical research. They add that the positivism stance is widely used in natural sciences and that social sciences premised by positivism require the use of scientific data collection and analysis methods. Similarly, Easterby-Smith et al. (2002) assert that the positivist is allied to the ontological assumption that reality is external and objective. Additionally, the epistemological assumption of a positivist is that knowledge is of significance only if the properties of its reality can be measured based on observations (Easterby-Smith et al., 2002). Saunders et al. (2019) also suggest that the positivist will search for causal relationships within the data and create law-like generalisations while applying a deductive approach to the research. Saunders et al. (2019) further argue that because the positivist strictly focuses on scientific empirical methods to generate pure data and facts that are independent of the researcher, highly structured methodologies are preferable to enable repeatability of the research following this philosophical stance.

The positivist philosophy was well-suited for this study due to its emphasis on objective observation, measurement, and quantitative analysis, which aligned with the methodological choices made. The use of survey questionnaires and field observations ensured that data was gathered through direct observation and measurement, aligning with the positivist principle of relying on empirical evidence (Fellows and Liu, 2015). Positivist research aims to establish generalizable laws and principles. By validating the developed pavement condition assessment method through a case study, the study sought to demonstrate the model's broader applicability, moving towards generalizability. Positivism employs established methods and techniques to ensure reliability and validity, such as the well-established survey questionnaire data collection method and Analytic Hierarchy Process (AHP) in the field of the built environment. Furthermore, the development of a pavement condition assessment method suggested an underlying interest in understanding the relationship between the novel method and gravel loss prediction models for unpaved roads, aligning with the positivist goal of identifying causal relationships between variables that can predict and explain phenomena (Saunders et al., 2019). While the identification of high-impacting road surface distresses might have involved some subjective judgment, the use of AHP provided an objective quantitative method for weighting and ranking the key road surface distresses, minimizing researcher bias and promoting objectivity.

In conclusion, the use of a positivist philosophy in this study was justified by its alignment with the chosen methodology and the desire for objective, quantifiable, and potentially generalizable findings. The emphasis on observable data, quantitative measurement, and model validation reflected a commitment to the principles of positivist research.

4.2.2 Interpretivism

Interpretivism is the opposite of positivism; it was developed in response to criticisms of the positivist stance. Collins and Hussey (2014) state that interpretivism rests on the ontological assumptions that social realities are created by humans and that these realities are subjective and multiple. Kulatunga (2008) simplifies this understanding by explaining that because humans are influenced by feelings and perceptions, they are complex and cannot be simply treated as objects. Easterby-Smith et al. (2015) add that interpretivism (social constructivism) encompasses the human understanding of their reality through sharing experiences using the medium of language. According to Kulatunga (2008), interpretivists do not search for causal relationships or for external factors but rather admire the different views and constructions that humans place on their experiences.

The interpretivist approach was not well-suited for this study, as it emphasizes understanding the subjective meanings individuals attach to their experiences (Collins and Hussey, 2014). In contrast, this study aimed to develop an objective pavement condition assessment method, applicable to various unpaved roads. The use of a survey questionnaire and Analytic Hierarchy Process (AHP) ensured a systematic and quantifiable approach, which was more closely aligned with positivist philosophy. Interpretivism typically involves qualitative methods, such as in-depth interviews, observations, or content analysis, to explore individuals' meanings and interpretations

(Kulatunga, 2008). Since this study collected data using survey questionnaires and deployed AHP to derive weightings, the quantitative focus of the study made interpretivism a less suitable choice. Furthermore, interpretivist research typically focuses on understanding phenomena within their specific contexts, recognizing that meanings and interpretations can vary across different settings. This study, however, sought to develop a generalizable pavement condition assessment method for unpaved roads, applicable beyond the specific case study. The pursuit of generalizability is not a primary goal of interpretivist research, as interpretivism typically prioritizes depth and richness of insight over generalizability and validation. The study's emphasis on validation and generalizability aligns more closely with the positivist philosophy.

In conclusion, while interpretivism can provide valuable insights into complex social phenomena, its emphasis on subjectivity, qualitative methods, social context, and depth of insight made it a less suitable philosophy for this study. The study's objectives, methodology, and context were more closely aligned with a positivist philosophy.

4.2.3 Pragmatism

Žukauskas et al. (2013) assert that pragmatism, on the other hand, does not belong to any philosophical system or reality and that this philosophical stance only deals with the facts. They add that pragmatists believe that research begins with identification of a problem and should be directed at developing practical solutions that inform future practice. Saunders et al. (2019) are of the view that with pragmatism, the combination of more than one philosophical assumption in the same research is acceptable and is dictated by the research topic. In addition, Žukauskas et al. (2013) suggest that pragmatists place a lot of emphasis on practical results with the researcher having the freedom to choose the data collection and analysis methods that best suit the research aims and objectives. Pragmatists believe that the truth is what is currently in action and that the researcher’s values drive the process of inquiry which is underpinned by the sense that there is a problem that must be solved (Žukauskas et al., 2013).

Pragmatism, with its emphasis on practical effectiveness and diverse methodological approaches, initially appeared suitable for this study. However, it ultimately proved illfitted. Pragmatism prioritizes context-specific, localized knowledge over universal, generalizable principles (Saunders et al., 2019). In contrast, this study aimed to develop a pavement condition assessment method that could be broadly applied across unpaved roads in Uganda. Furthermore, pragmatism often involves collaborative and participatory engagement with stakeholders, which was not the case in this study. The research employed a more structured survey questionnaire, rather than the level of collaborative engagement typical of pragmatic research.

In conclusion, while pragmatism can be a valuable philosophy for many studies, its emphasis on stakeholder engagement, local knowledge, and contextual adaptation rendered it less suitable for this study. The study's focus on developing a standardized, quantifiable, and generalizable pavement condition assessment method for unpaved roads aligned more closely with a positivist philosophy.

4.3 Research Approach

According to Saunders et al. (2019) it is important for the researcher to identify which research approach; categorised as deductive, inductive and abductive approaches; are applicable to the study. This line of thought is supported by Awuzie and McDermott (2017) who mention that the choice of research approaches is essential at the initial stages of the research study. They add that this is because the approach provides the basis against which the structure of the research design is developed with the aim of effectively providing answers to the study’s research questions. The deductive, inductive and abductive approaches are discussed in the following sections.

4.3.1 Deductive approach

With the deductive approach, a conceptual and theoretical research structure is developed and then tested through empirical observation, aimed at verifying whether the theory applies to specific instances (Collins and Hussey, 2014; Mohd Nawi, 2012). Simply put, the deductive approach begins with the general and ends with the specific i.e., from *“top to bottom”*. This research adopted a deductive approach, progressing from broad pavement management theories and concepts to the specific development of a pavement condition assessment method for the Ugandan unpaved road network, as depicted in Figure 4.2.

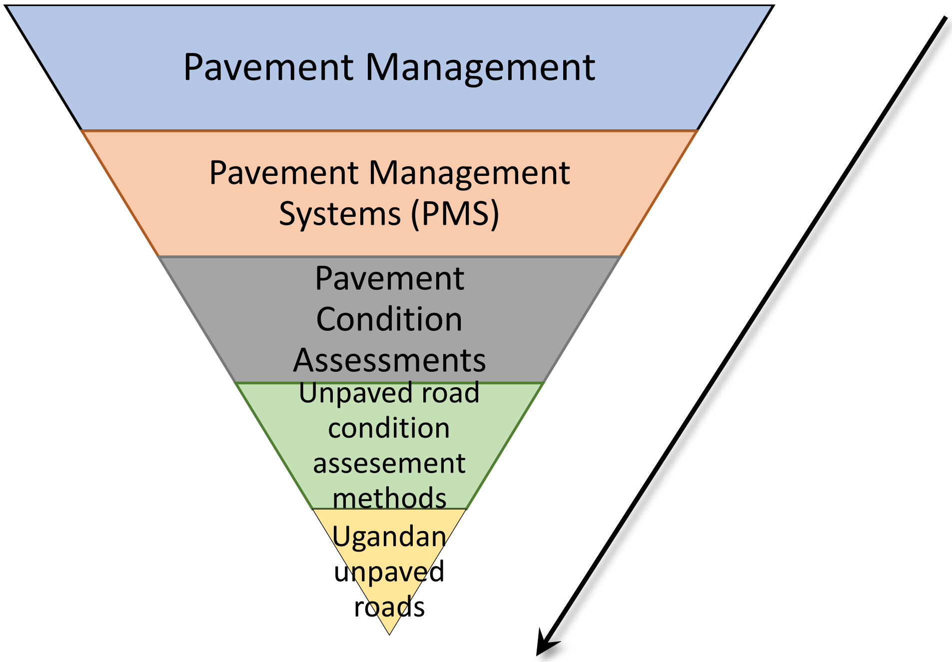


Figure 4.2: The deductive approach of the literature review in Chapter 2 of this PhD research study

The systematic and logical organization of the study, with clear objectives, rigorous methodology, and quantifiable outcomes, made the deductive approach well-suited for this research. Furthermore, the validation and application of the developed model on a case study road demonstrated its practical utility, aligned with the deductive reasoning process employed. The deductive approach provided a structured and methodical framework for creating a quantifiable and objective pavement condition assessment method for unpaved roads. By moving from general principles to specific factors and utilizing a robust methodology, the study ensured the development of a valuable method for unpaved road maintenance management.

4.3.2 Inductive approach

The inductive approach on the other hand builds theories from specific facts obtained from observation of empirical reality to draw general conclusions which is the opposite of deduction (Collins and Hussey, 2014). With the inductive approach, the researcher starts from the specific to the general i.e., *"bottom-up"* approach. The inductive approach was not well-suited for this study because inductive research typically involves a more open-ended and exploratory process, where the data guides the research direction (Saunders et al., 2019). In contrast, this study employed a more structured methodology with predetermined indicators and data collection methods. This structured approach was necessary to ensure the development of a standardized and quantifiable pavement condition assessment method. Additionally, inductive research often involves generating new theories or concepts based on the observed data (Collins and Hussey, 2014). However, this study drew upon existing literature and established theories of road condition assessment to inform the development of the model. The objective was not to build new theory but to apply existing knowledge to create a practical pavement condition assessment method for unpaved roads in Uganda.

Ultimately, the study's methodology aligned more closely with a deductive approach and positivist philosophy. The use of established theories, predetermined indicators, structured data collection methods, and a focus on generalizability are characteristic of deductive reasoning and positivism. These attributes contrast with the exploratory, context-specific, and theory-building nature of the inductive approach.

4.3.3 Abductive approach

Saunders et al. (2019) and Awuzie & McDermott (2017) agree that the abductive approach enables researchers to move back-and-forth between theory and data to modify an existing or develop a new theory. Saunders et al. (2019) add that while the abductive approach could be viewed as a combination of deduction and induction, the flexibility of an abductive approach implies that it can be used across several research philosophies. The abductive approach was however not well suited for this study because abduction relies on subjective interpretation of observations to generate hypotheses. This study, in contrast, emphasized objective measurement and quantitative analysis through survey questionnaires and AHP, minimizing researcher subjectivity. Furthermore, the abductive approach is often context-specific and may lack the generalizability that was an important outcome of this study. It should be noted that this study, aimed to develop a generalizable pavement condition assessment method applicable to various unpaved roads in Uganda. Additionally, the abductive approach is inherently uncertain and tentative, as multiple explanations may fit the observed data (Saunders et al., 2019). This study, however, aimed to develop a standardized and reliable pavement condition assessment method, requiring a more definitive and less ambiguous approach than what abduction could offer.

4.4 Methodological Choice

Researchers Amaratunga et al. (2002), Bryman (2012) and Melnikovas (2018), have traditionally distinguished research choices along the quantitative and qualitative divide. These researchers assert that quantitative research is synonymous with the positivist philosophy underpinned with objectivist ontology, while qualitative research is premised on interpretivist philosophy and constructivist ontology. A simplistic distinction proposed by Bryman (2012) states that quantitative research emphasizes measurement and quantification during data collection and analysis while qualitative research accentuates words rather than numbers in the collection and analysis of data.

Saunders et al. (2007) in contrast argues that the methodological choice adopted by the researcher varies from simple to complex based on the nature of study. They add that three choices are prevalent in management research i.e., mono method, multi-method, and mixed method as illustrated in Figure 4.3.

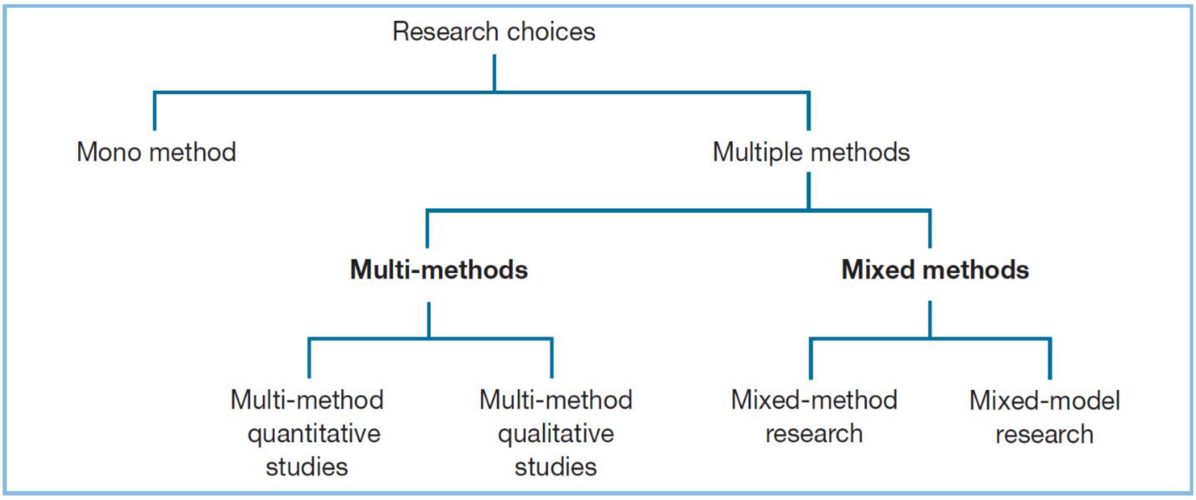


Figure 4.3: Research Choices (Saunders et al., 2007)

The mono method applies a singular data collection and analysis technique which is either a quantitative or a qualitative method used on its own. The multi-method on the other hand combines multiple data collection techniques used in a way that is either “qualitative only” or “quantitative only” (Alfar, 2016). For example, a researcher may collect data using both structured observation and questionnaires and analyse this data using statical quantitative procedures, such a study would be deemed a multi-method quantitative study (Saunders et al., 2007). Mixed methods, however, differ from multi-methods because they use both quantitative and qualitative data collection and analysis techniques during the research study.

This PhD research study utilized a multi-method *(quantitative only)* methodological choice due to the complementary nature of the quantitative techniques employed, such as surveys, Analytic Hierarchy Process, and a case study for validation. While all quantitative in nature, each method addressed a distinct aspect of the research, bolstering the overall rigor and validity of the developed pavement condition assessment model. Furthermore, the application of these diverse quantitative methods, which are grounded in a positivist and deductive philosophy, suggests that the study benefited from a more comprehensive and robust approach. The survey questionnaires provided the raw data, AHP established objective weights for the individual distresses, and the case study validated the practical application of the model. This multi-method quantitative choice enhanced the reliability, validity, and overall quality of the developed pavement condition assessment model.

4.5 Research Strategies

According to Johannesson and Perjons (2014), the research strategy is a plan that guides the researcher to answer the research question and achieve the objectives. They add that the research strategy is a high-level guide that must be complimented by detailed research methods or techniques such as interviews, questionnaires and focus groups. The choice of strategy is dependent on the purpose of the research, extent of existing knowledge, the available time and resources, and the philosophical stance of the research (Saunders et al., 2019). Given the positivist philosophical orientation of this PhD research study, which emphasizes objective observation, measurement, and quantitative analysis to establish generalizable principles, this section will review the relevant research strategies. The key strategies, including survey, experiment, case study, and archival analysis, are discussed in the following sub-sections as they pertain to built environment research studies.

4.5.1 Survey

Surveys are one of the most commonly used research strategies in construction engineering and management constituting up to 22% of the research strategies deployed in built environment research studies (Taylor and Jaselskis, 2010). Collins and Hussey (2014) assert that surveys are designed to collect data from a sample with the aim of generalising the results to the entire population. They add that though surveys are traditionally associated with positivist underpinnings and quantitative research, they are also widely applied in qualitative research employing data collection techniques such as interviews and observations.

Saunders et al. (2019) observe that questionnaires are widely used in surveys because they are economical, cover a wide range of respondents in different geographical locations and allow for standardisation of the data. Additionally, the survey strategy is easy to understand and explain because it accords the researcher control over the data collection process. Johannesson and Perjons (2014) add that surveys are popular because they are inexpensive and can be used to collect both quantitative and qualitative data. However, the disadvantage of surveys is that they have low response rates from participants, can be time consuming during the data analysis stages and may at times provide superficial results if the data collection instrument is not well designed (Johannesson and Perjons, 2014). Surveys can, however, be administered electronically which can assist with data analysis.

4.5.2 Experiment

According to Johannesson and Perjons (2014), experiments are empirical studies aimed at establishing cause and effect relationships. These relationships can be formulated as a hypothesis stating, for example, that “variable A causes outcome B”. Similarly, Collins and Hussey (2014) state that experiments investigate the relationship between dependent and independent variables by way of laboratory or field experiments. This research strategy is generally associated with natural sciences underpinned by positivism and quantitative research designs. This is because laboratory experiments require the researcher to have control over the research process to identify that one variable has an effect on another without the influence of other external factors (Saunders et al., 2019).

The experiment strategy was not suitable for this PhD research study because experiments require the researcher to have control over one or more variables and the research question should seek to establish causal relationships. Developing an improved road condition assessment method required employing data collection methods such as questionnaires which made it impractical to control any of the variables.

4.5.3 Case Study

A case study is defined by Collins and Hussey (2014) as a strategy that can be used to explore a topic or phenomenon *(the case)* within its natural setting by deploying various data collection techniques to obtain an in-depth understanding of the topic. Johannesson and Perjons (2014) assert that a case study research strategy should *(1)* focus on a single topic, *(2)* provide in-depth knowledge, *(3)* study a phenomenon in its natural setting, *(4)* holistically study relationships within the topic and *(5)* make use of multiple information sources. They add that case studies may be used for different purposes such as exploratory, descriptive, and explanatory studies. Exploratory case studies seek to generate research questions or hypotheses in a new study area while descriptive case studies aim at producing in-depth and rich descriptions of the topic (Johannesson and Perjons, 2014). The explanatory case studies not only provide descriptions but also identify causal relationships within the research topic or phenomenon (Johannesson and Perjons, 2014).

Saunders et al. (2019) contend that the key factor in defining the case study strategy is the choice of topic and determining the boundaries of the study. They add that the researcher must understand the dynamics of the topic by critically reviewing the interactions between the phenomenon and its context. In contrast, Collins and Hussey (2014) assert that a successful case study strategy requires the researcher to; select a case that encompasses issues of interest, carryout preliminary investigations, collect data using techniques such as observations, interviews, archival data etc., and finally analyse the data. Case studies have however been criticized for their dependency on single case exploration which makes it difficult to apply a scientific generalisation of the observed phenomenon (Zainal, 2007).

4.5.4 Archival and documentary research

The archival research strategy relies on the use of an organisation's archival data, such as emails, letters, reports, memos, policy statements, publications etc. to undertake an empirical study and data analysis (Mohd Nawi, 2012). Saunders et al. (2019) mentions that the documents used in an archival strategy are considered secondary sources because these documents are originally created for a different purpose. The researcher should therefore be mindful of the fact that the archival data was not created for the specific research study being carried out (Saunders et al., 2019).

The use of the archival research strategy has several advantages. Das et al. (2017) point out that one of the most glaring advantages is the low cost of acquisition and ease of availability of archival data. They add that an organisation's documents provide a rich set of data that is "ready-to-go" implying that significant time savings are made by the researcher. Saunders et al. (2019), however, cautions that the effectiveness of this strategy is dependent on the availability and accessibility of the archival data. They advise that for situations where there are inconsistencies in the data, the archival research strategy should be combined with another strategy such as a case study or survey.

4.6 Time Horizon

The research time horizon focuses on the duration of the study with emphasis on the time required by the researcher to achieve the aims and objectives of the study. Saunders et al. (2019) states that the time horizon of any research can either be cross-sectional or longitudinal. Cross-sectional studies aim at establishing relationships of a topic or phenomenon at a particular point in time often deploying a survey strategy to achieve the research objectives (Saunders et al., 2019). Longitudinal studies on the other hand, attempt to establish trends and relationships within the research topic over a prolonged time period. This PhD research study adopted the cross-sectional time horizon due to the researcher's time and resource constraints.

4.7 Research design for this study

This study aims to develop an improved condition assessment method for unpaved roads in Uganda. To achieve this aim, specific objectives were established, and the research design was the overall plan of how these objectives would be realized. The research design sets out the sources, tools, and methods of collecting and analysing the data required to meet the aim of the research study (Saunders et al., 2019). Figure 1.2 shows the process which this researcher followed to achieve the study's aim and objectives. The study was carried out in five (05) stages i.e., research formulation, investigation, model development, model validation and recommendations. These stages are discussed in the following subsections.

4.7.1 Stage 1: Research formulation

According to Sattineni (2014), a detailed review of literature is often the first stage of an academic research study. To gain State-of-the-Art knowledge in pavement management and PMS, a wide-ranging literature review was carried out with particular focus on pavement condition assessment methods as discussed in Chapter 2. The wide-ranging literature review facilitated the establishment of the research aim, objectives, and methodology. The previous literature review Chapters 2 and 3 presented a critical review of the unpaved road condition assessment methods and the status of pavement management for unpaved roads in Uganda. Additionally, Chapter 3 reviewed the existing literature regarding prediction models for pavement deterioration with particular emphasis on gravel loss prediction models. The findings from the literature review enabled this researcher to clearly define the problem statement by identifying the gaps within condition assessment methods for unpaved roads in Uganda.

4.7.2 Stage 2: Investigation

The second stage involved data collection by means of questionnaires. These questionnaires were distributed through emails to participants located in different regions within the country. The questionnaire survey was designed to align with the objectives of the study to identify the high impacting road surface distresses on unpaved roads in Uganda. During this stage, a pilot survey was conducted to obtain initial feedback from a select group of participants to ensure that the survey questions were appropriate for obtaining the research objectives. Data obtained from the questionnaire survey was analysed leading to weighting and ranking of the high impacting road surface distresses on unpaved roads in Uganda. The questionnaire survey data collection method offered cost-effectiveness, rapidness, and the ability to cover a wide range of respondents in different geographical locations allowing for standardisation of the data. This quantitative data collection method is comprehensively discussed in subsection 4.8 below.

4.7.3 Stage 3: Development of the GRCI model

At stage 3, the data collected from stage 2 was used to develop a mathematical model, termed the Gravel Road Condition Index (GRCI), that takes into account the weighting factors of each individual road surface distress. The GRCI was developed by deploying the Analytic Hierarchy Process (AHP) to convert the subjective survey results into objective mathematical data. Crucially, the developed GRCI determined the overall condition rating of an unpaved road network, provided a condition rating of each section of assessed road length and classified a road section into one of the five condition categories for statistical representation. Chapter 6 of this thesis adequately describes the steps taken by this researcher to develop the GRCI model.

4.7.4 Stage 4: Validation of the GRCI model

Stage 4 involved validating the developed GRCI *(in stage 3)* by applying the method on a case-study gravel road (i.e., by field observation) and verifying the results through comparison with pre-existing condition assessment methods in Uganda. The GRCI model was validated through application of the model on the Misindye-Kiyunga Road with results showing that the model provided a representative condition rating for the unpaved road. Stage 4 also included determining the Annual Gravel Loss (AGL) of the case-study road to establish a relationship between the AGL and GRCI. This was done by establishing a linear regression model that described the relationship between the dependent variable, AGL, and the independent variable, GRCI. The AGL versus GRCI relationship is further discussed in Chapter 7 of this thesis.

4.7.5 Stage 5: Conclusions and recommendations

The last stage involved a review of how the study’s aims and objectives were achieved while also illustrating the research study’s contribution to both theory and practice. This stage was crucial as it represented an overview of what the study was meant to achieve and also discussed the recommendations for further study in pavement condition assessments for unpaved roads. This stage also highlighted the limitations of the research study.

4.8 Quantitative data collection method

According to Lee (2002), quantitative data collection methods assist researchers in the built environment to search for causal explanations and fundamental laws that reduce the whole into the simplest elements to facilitate analysis. This research study has deployed a questionnaire survey which is a quantitative data collection method to enable this researcher obtain data regarding the high impacting road surface distresses on unpaved roads in Uganda. This quantitative data collection method is discussed in the succeeding subsections.

4.8.1 Questionnaire survey

The survey research strategy mentioned in subsection 4.5.1 is popular for built environment research studies (Taylor and Jaselskis, 2010). For a survey, questionnaires are the most used data collection technique comprising a set of questions with a choice of answers which are employed to obtain information from participants (Boadi, 2020). According to Saunders et al. (2019), questionnaires can be delivered and collected from participants through the internet, post, SMS (text message), telephone or face-to-face (Figure 4.4).

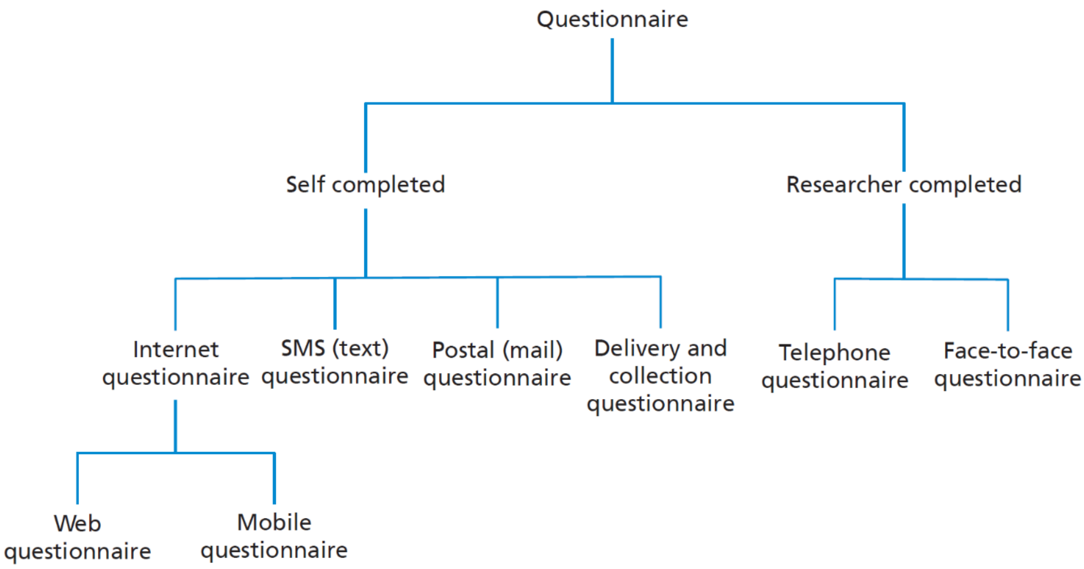


Figure 4.4: Questionnaire modes of delivery (Saunders et al., 2019)

This researcher reviewed the available modes of delivery and made use of the internet to deliver emails containing a pdf fillable version of the questionnaire to each participant.

4.8.2 Selection of target participants and sample size

Saunders et al. (2019) states that because it is impracticable to collect data from an entire population, sampling makes it possible for a researcher to statistically generalize the data obtained from a pre-determined sample size. Being that this research study aims at developing a road condition assessment method for unpaved roads in Uganda, this researcher considered a sample size of 23 districts to represent the 136 districts *(shown in Figure 4.5)* in the entire Country. The sample size of 23 districts was carefully selected to ensure that all six (06) regions of the Country were represented. The rationale of the selection of participants follows the fact that the Uganda National Roads Authority (UNRA) maintains 15,227 km of unpaved roads representing 75% of the National Road network through its district stations located in all six (06) regions of the Country (UNRA, 2022).

Table 4.3: List indicating the regional location of the 23 district stations managing the UNRA National Road network

Central Region	**Eastern Region**	**Northern Region**	**South-Western Region**	**Western Region**	**North-Eastern Region**
80.Kampala	74.Jinja	3.Arua	118.Ibanda	113.Fort Portal	41.Soroti
100.Luwero	63.Mbale	16.Gulu	136.Kabale	105.Hoima	21.Kotido
84.Masaka	55.Tororo	18.Kitgum	120.Kasese	103.Masindi	22.Moroto
82.Mpigi		32.Lira	125.Mbarara		
94.Mubende		10.Moyo			

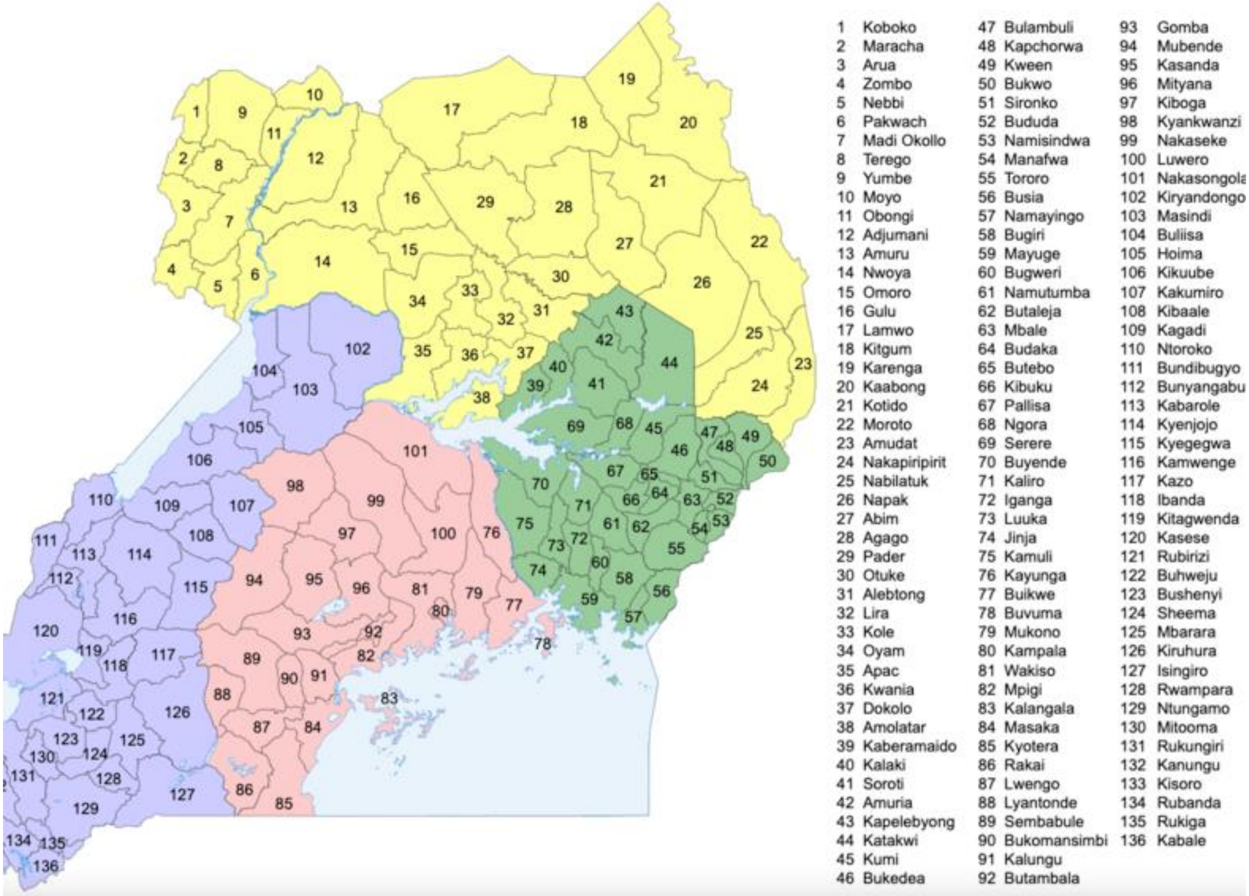


Figure 4.5: Map of Uganda indicating all the 136 districts in the Country (UNRA, 2022)

The Directorate of Road Maintenance in UNRA maintains unpaved roads through the 23 district stations *(shown in Table 4.3)* spread across the Central, Eastern, Northern, South-western, Western and North-eastern regions of Uganda using force-account and works contractors (UNRA, 2022). Each of the Stations has a minimum of two (02) road maintenance engineers tasked with carrying out regular pavement condition assessments for the unpaved road network within their jurisdiction.

It is important to note that each of the 23 district stations act as headquarters for the remaining districts in the Country with regard to the UNRA National Road maintenance. Additionally, this researcher included participants under District Local Governments (i.e., DUCAR representatives) from the corresponding 23 districts listed in Table 4.3 who are not under the UNRA jurisdiction. This was done to ensure that DUCAR engineer's industry experiences and knowledge on the high impact road surface distresses for unpaved roads in Uganda were adequately captured by the research study.

In summary, a total of 70 participants were selected for this research study, representing approximately 3 participants from each of the 23 sample districts in Uganda. The participants were carefully chosen to ensure that all six regions of the country were represented, as shown in Table 4.4. It is important to note that the questionnaire targeted a very specific group of engineering professionals, namely road maintenance engineers and road inspectors, who are limited in number and dispersed across the various districts in the country.

Table 4.4: Number of Participants from each of the six (06) regions in Uganda

Region of Uganda	**Number of Participants**		
	UNRA	**DUCAR**	**Total**
Central Region	10	5	15
Eastern Region	6	3	9
Northern Region	10	5	15
South-Western Region	8	4	12
Western Region	6	4	10
North-Eastern Region	6	3	9
Total	**46**	**24**	**70**

4.8.3 Questionnaire design

The self-completed questionnaire *(attached as Appendix D)* was developed and divided into two major parts i.e., Part A: Participant background information and Part B: High impact road surface distresses for unpaved roads. Part A of the questionnaire was designed to obtain information on the participant's background and their organization's road condition assessment practices. Part B on the other hand was the crux of the questionnaire intended on establishing the high impact road surface distresses for unpaved roads in Uganda. The results from the questionnaire survey are presented in the subsequent chapter including the validity and reliability considerations of the survey.

According to Boadi (2020), the Likert scale is an ordinal scale used in questionnaire surveys to enable researchers measure variables and indicators of the participants based on predetermined statements that categorise responses on a scale of importance. This research study deployed the Likert scale *(indicated in Table 4.5)* to establish the road surface distresses which have the highest impact on the condition rating of unpaved roads in Uganda.

Table 4.5: Value designation for Likert scale used in this study

Scale of distress Impact	**Insignificant impact**	**Minor impact**	**Moderate impact**	**Major impact**	**Severe impact**
Value	1	2	3	4	5

The values assigned to the 5-point Likert scale of distress impact range from 1 to 5 as indicated in Table 4.6 i.e., 1 = Insignificant impact, 2 = Minor impact, 3 = Moderate impact, 4 = Major impact and 5 = Severe impact. This researcher found the 5-point Likert Scale most suitable for this research study because of its ease of use and its grounded familiarity in pavement maintenance research. For example, Alfar (2016) utilized the 5-point Likert Scale while investigating the impacting factors of pavement maintenance in the UK and demonstrated that the scale was reliable, comprehensible, and offered clarity to the participants. Aburas (2020) also adds that the 5-point scale offered improved correlation and central tendency than the scales with fewer values.

4.8.4 Pilot Survey

According to Saunders et al. (2019), using a questionnaire to collect data should first be pilot tested on a select group of participants prior to circulation. The purpose of the pilot survey is to refine the questionnaire through obtaining initial feedback from a select group of participants to ensure that the survey questions are suitable and appropriate to obtain the research objectives. In this research study, the researcher disseminated draft questionnaires to six (06) experienced, road maintenance industry practitioners whose feedback on the research questions was incorporated in the final questionnaire. The primary aim of the pilot survey was to test the appropriateness of the survey questions in establishing the high impact road surface distresses for unpaved roads in Uganda.

The response rate from the six (06) participants was 100% and the feedback was that the questionnaire was appropriate to meet the objectives of study by establishing the road surface distresses which have the highest impact on the condition rating of unpaved roads in Uganda using the 5-point Likert Scale discussed in subsection 4.8.3. The pilot survey also enabled the researcher to statistically analyze the data collected using the *"mean weight method"* adopted by Odu (2019) to determine the ranking and weight factors of the nine (09) distresses.

The pilot survey also established that the mean score technique based on the 5-point Likert Scale (1 = Insignificant impact and 5 = Severe impact) could be used to calculate the mean score of each distress. The results from the pilot survey confirmed to the researcher that the questionnaire could be used in the main survey to obtain reliable data to meet the objectives of the study. The feedback from pilot survey participants enabled this researcher to adjust the minor errors that were discovered in the draft questionnaire.

4.8.5 Validity and Reliability test

According to Aithal and Aithal (2020) the questionnaire design and development model shown in Figure 4.6 includes two important elements i.e., Reliability and Validity.

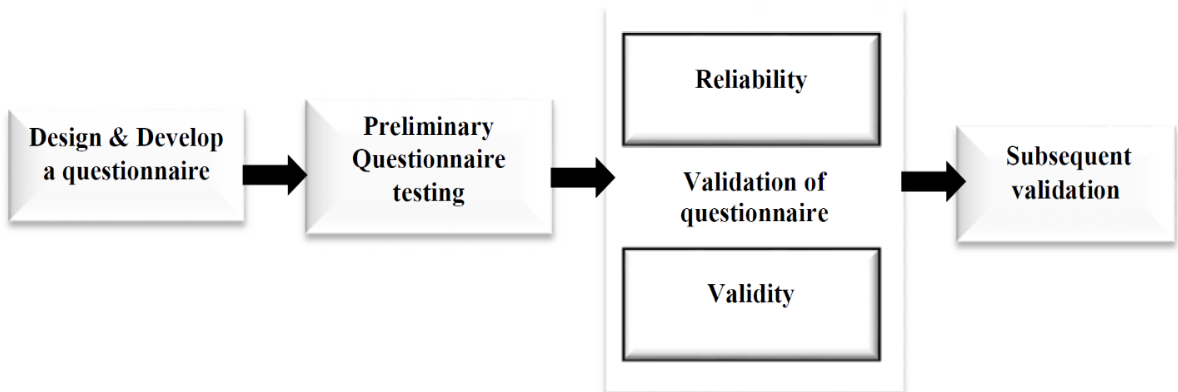


Figure 4.6: Questionnaire design and development model (Aithal and Aithal, 2020)

Establishing the degree of reliability and validity of the questionnaire is key for a researcher to establish the trustworthiness of the survey results. A valid questionnaire enables the researcher collect accurate data that wholistically measures the items in question (Saunders et al., 2019). A reliable questionnaire, on the other hand, informs the researcher that the data collected is consistent and free from miscomprehension (Saunders et al., 2019). This researcher has therefore undertaken reliability and validity checks on the survey results as elaborated in the subsequent subsections.

4.8.6 Validity test

According to Taherdoost (2018), the validity test of a questionnaire measures how well the collected data covers the actual area of investigation i.e., “measure what should be measured” (Taherdoost, 2018). Similarly, Alfar (2016) asserts that validity ascertains whether a researcher has measured what they set out to measure. He adds that validity can be analyzed through any of these four (04) methods namely; (1) face validity, (2) construct validity, (3) content validity and (4) criterion validity. For this study, face validity, criterion validity and construct validity have not been used because these tests can be determined using a dichotomous scale that uses *yes* and *no* options to designate favorable or unfavorable items, respectively (Aithal and Aithal, 2020). Due to the resource and time constraints, this has not been carried out by the researcher. This researcher however tested the research questionnaire for content validity.

Content validity involves examining the items in the questionnaire to check whether they represent the entire theoretical construct of the research questions under consideration (Aithal and Aithal, 2020). This is done by a panel of experts who possess adequate expertise and experience in the content construct to fully examine and evaluate the items under investigation. For this study, this was done through carrying out a pilot study that sort the opinions of six (06) experts in the field on road maintenance management. The experts checked the questionnaire items for their adequateness in measuring the content construct of the study. Following feedback form the experts, the questionnaire items were refined and important items that were missed in the original questionnaire were added to create the final questionnaire that was eventually issued to participants after completing the content validity.

4.8.7 Reliability test

The reliability of the questionnaire had to be checked by this researcher to ensure that the survey results were consistent. Reliability testing also enables a researcher identify errors in the samples and capture the demographical characteristic variations of the participants (Aithal and Aithal, 2020). According to Alfar (2016), reliability tests can be carried out using three (03) methods i.e., test re-test method, alternative form method and the internal consistency approach. The test re-test method and alternative form methods were found to be inappropriate for this study because they require participants to complete the questionnaire twice at different points of time leading to research repetition. Both methods could therefore not be used due to the limited resources and time constraints of the research study. Due to these reasons, this researcher found the internal consistency method most appropriate for testing the reliability of the survey results.

According to Aithal and Aithal (2020) the internal consistency method measures the inter-correlation of the questionnaire items and is also a consistency measurement for the intended construct of the questionnaire. They add that the most used method for measuring internal consistency is the Cronbach's Alpha coefficient which ranges from zero (0) to one (1). A zero value of the Cronbach's Alpha indicates no internal consistency i.e., the items in the questionnaire are not correlated with one another. Higher values on the other hand indicate strong interrelated relationships between the questionnaire items with a Cronbach's Alpha value of one (1) indicating perfect internal consistency. This researcher carried out a reliability test using Cronbach's Alpha coefficient and obtained a high value of internal consistency as discussed in Chapter 5.

4.9 Case study data collection method

According to Lee (2002), researchers should investigate phenomena within their real-world contexts and engage in direct, intensive examinations of research settings to gain contextual understanding. This study applied the developed pavement condition assessment model to a specific case study road to practically validate and demonstrate its effectiveness in a real-world setting. The quantitative data collection method utilised is discussed in the subsequent subsections.

4.9.1 Case study method

The case study method has enormous relevance in built environment research because it's carried out in *"real world"* conditions (Lee, 2002). This research study validated the developed GRCI model by applying the method on a case-study gravel road and verifying the results through comparison with pre-existing condition assessment methods in Uganda. The case-study road *(Misindye-Kiyunga Road)* was selected using the criteria set out in subsection 4.9.2. Additionally, the case-study gravel road provided Annual Gravel Loss (AGL) data that was used to establish a relationship between the AGL and GRCI. The results from the case-study field observation are discussed in Chapter 7.

4.9.2 Criteria for the selection of case study

According to Akoh (2018), the criteria for the selection of a case study for investigation should consider the following criteria;

- Relevance to the research aim and objectives.
- Diverse across contexts.
- Study the complexity of the context within which the case study exists.
- Data accessibility.

Following the above rational, this researcher selected to apply the GRCI model on the Misindye-Kiyunga Road which is 11km long, due to the following reasons;

- The road exhibited all the nine (09) identified distresses in all the 11 sections.
- The road carries low to medium traffic with dual functionality.
- The existing road is more than 6 meters wide in all the 11 sections.
- Traffic and existing road condition information was readily available from UNRA (2019).

4.10 Summary research objectives and methods adopted for data collection

This subsection provides a summary for the research objectives and methods adopted for data collection. The quantitative data collection methods applicable to this study have been discussed in the preceding sections and are summarised in Table 4.6.

Table 4.6: Research objectives and methods adopted for data collection

S/N	Research objectives	Literature review	Questionnaire	Case-study
1	Investigate current pavement condition assessment methods for unpaved roads and their related challenges.	X		
2	Review, identify and rank the high impacting road surface distresses that affect the condition rating of unpaved roads in Uganda.		X	
3	Develop a pavement condition assessment method, termed the Gravel Road Condition Index (GRCI), that will determine the condition rating of an unpaved road while also predicting future deterioration.	X	X	
4	Validate the GRCI and its application in Uganda.			X

4.11 Ethical Considerations

According to Saunders et al. (2007), ethics refers to the appropriateness of a researcher's behaviour in relation to the rights of the participants or subjects. They add that it is important for a researcher to take into account the ethical considerations at all stages to ensure that the research study is morally defensible. Saunders et al. (2007) state that the conduct of a student researcher should be guided by their university's code of ethics or ethical guidelines. This researcher has followed the University of Salford's Academic Ethics Policy and ensured that all the participants were provided with adequate details regarding the research study. This researcher also provided consent forms (Appendix E) and a participant invitation letter (Appendix F) to each of the participants to ensure that participant's involvement in the study was voluntary and in accordance with the university's academic ethics policy.

This researcher also obtained ethical approval from the University's ethics panel after satisfying all the ethical requirements to proceed with data collection involving engagement of participants. The ethics approval from the *"Ethics App"* (online) is attached as Appendix C of this thesis.

4.12 Summary of Chapter

This PhD research study adopted two data collection techniques, namely: questionnaires and case-study based field observation. Questionnaires have been used to collect data regarding the high impact road surface distresses that affect the condition rating of unpaved roads in Uganda. Data collected from industry practitioners, such as road maintenance engineers and road asset managers, in the survey was used to establish the weighting factor and severity combination required to develop the Gravel Road Condition Index (GRCI). The next chapter will present the results from the questionnaire survey.

Validating the developed GRCI method was done by applying the new method on a case-study road network (i.e., by field observation) and verifying the results through comparison with pre-existing condition assessment methods in Uganda. The researcher also established a relationship between the novel pavement condition assessment method (i.e., the GRCI) and the gravel loss prediction model for unpaved roads in Uganda using data obtained from the case-study based field observations.

Chapter Five

ESTABLISHING THE HIGH IMPACT ROAD SURFACE DISTRESSES VIA QUESTIONNAIRE BASED SURVEY

5.1 Introduction to the Questionnaire Based Survey

This research study adopted two data collection techniques, namely: questionnaires, and case-study based field observation. One of the research objectives of this study included reviewing and identifying the high impacting road surface distresses that affect the condition rating of unpaved roads. A questionnaire-based survey was therefore used to collect data regarding the nine (09) high impact road surface distresses that were identified following a comprehensive literature review. Data collected from industry practitioners, such as road maintenance engineers, technicians and road inspectors, was used to establish the weighting factor and severity combination required to develop the Gravel Road Condition Index (GRCI). The results from the questionnaire survey are presented in this chapter including the validity and reliability considerations of the survey.

5.2 Response Rate

Having distributed questionnaires to 70 participants through emailing a pdf fillable version of the questionnaire to each participant, the initial response rate was relatively low. However, following two phases of email reminders, the response rate increased significantly with 36 of 70 issued questionnaires being returned fully answered which represented a response rate of 51.4%. This response rate of 51.4% was considered sufficient for this type of study because Root and Blismas (2003) established that response rates between 20 to 25% were deemed acceptable for built environment research. Furthermore, this researcher noted that the 36 participants who returned questionnaires were located in at least one of the 23 districts that are representative of all the six regions in Uganda.

Of the 36 participants who returned fully complaint questionnaires, 80.56% worked for the Uganda National Roads Authority (UNRA), 5.56% for the Uganda Road Fund (URF) and 13.89% worked for District Local Governments (i.e., DUCAR representatives) as shown in Figure 5.1.

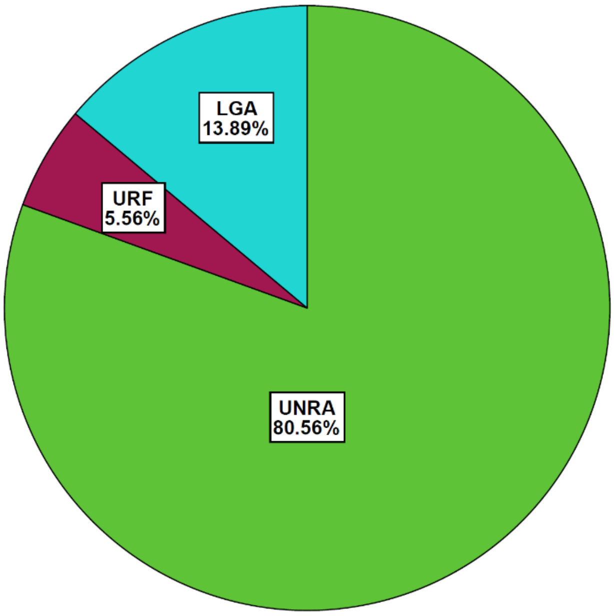


Figure 5.1: Survey response distribution per organization

5.3 Attributes of Participants

Part A of the questionnaire issued to the participants was used to obtain background information on the participants involved in the research study. Figure 5.2 indicates that 38.89% of the participants had a master's degree as their highest academic qualification. The participants that held a post graduate diploma as their highest academic qualification were 30.56% while those with an undergraduate degree were also 30.56%. It is important to note that all the participants in the survey had at least one undergraduate academic degree in civil engineering.

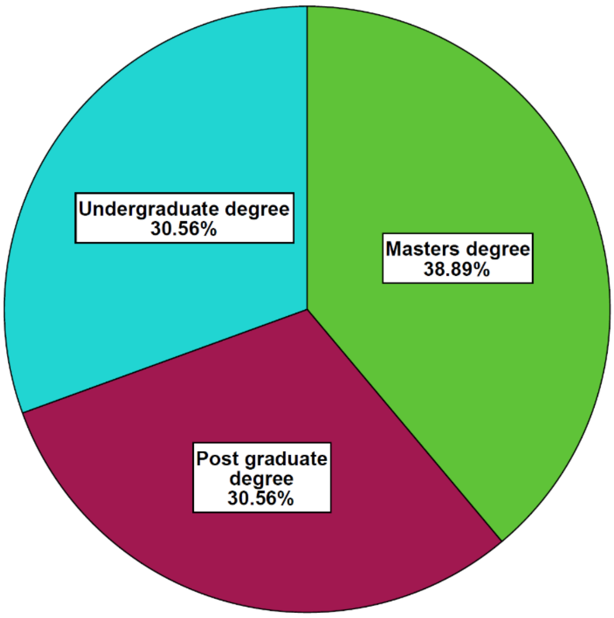


Figure 5.2: Highest academic qualification of participants

Participants were also required to indicate the years of experience worked in the road sector. Results from the survey revealed that 61.11% of the participants had more than 10 years' work experience. 30.56% of the participants had 5 to 10 years work experience and only 8.33% had less than 5 years' work experience as shown in Figure 5.3.

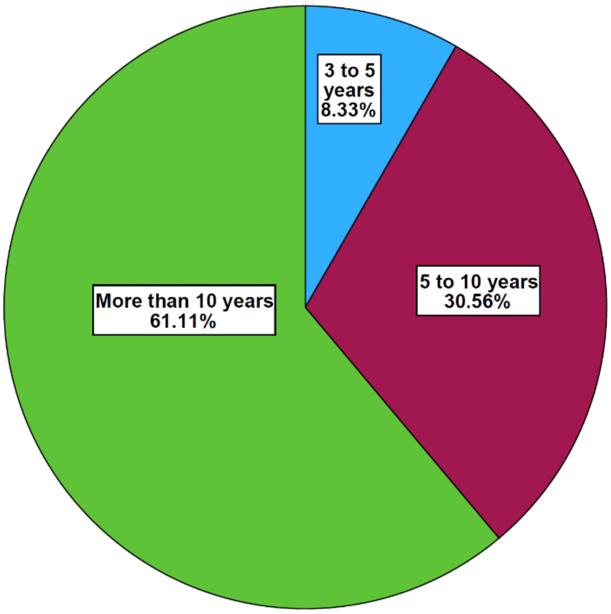


Figure 5.3: Participant experience in the road sector

Regarding the length (km) of unpaved roads under a participant's management, results from the survey shown in Figure 5.4 indicated that 13.89% of the participants managed between 14,000km to 16,000km, 8.33% between 2,000km to 14,000km and 77.78% between 0 to 2,000km. The participants that managed more than 14,000km were regional road maintenance managers that had several junior maintenance engineering staff under their regional jurisdiction. The reminder of the participants were on average responsible for carrying out road condition assessments of at least 570 km of unpaved road network. This informed the researcher of the average road network length covered by each Designated Agency (DA).

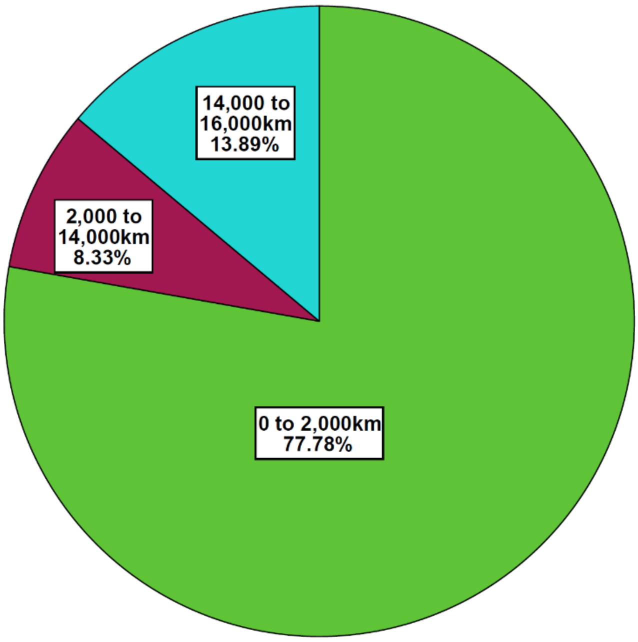


Figure 5.4: Length (km) of unpaved roads under a participant's management

5.4 Participant's organization results on unpaved pavement condition assessment practices

The questionnaire issued to the participants also required information on the pavement condition assessment practices of the participants' organization. This data would enable the researcher to comprehend the improvements required in the pavement condition assessment methods currently in use by road agencies in Uganda.

Results from the survey indicated that 100% of the participant's organizations collected road condition data using a pavement condition assessment method for unpaved roads. 50.00% of the participants were collecting pavement condition data using the Visual Condition Index (VCI) while 41.67% were using the Ministry of Works and Transport (MoWT) Condition Rating *(see Figure 5.5).* The Annual District Inventory and Condition Survey (ADRICS) was also being used by 8.33% of the participants many of whom are employed by DUCAR agencies.

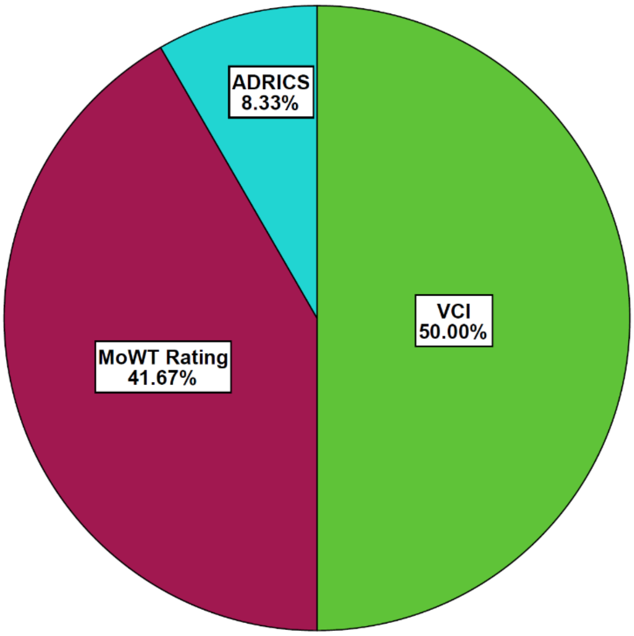


Figure 5.5: Pavement condition assessment methods currently in use by road agencies in Uganda

Participants were also required to rate the ease of using their organization's unpaved condition assessment method on a 5-point Likert Scale where, 1 = very easy and 5 = very hard. Results showed that 47.22% of the participants found their pavement condition assessment method *fair* to use with 16.67% and 25.00% finding their pavement condition assessment methods *easy* and *very easy* to use respectively. 8.33% and 2.78% of the participants found their pavement condition assessment method *hard* and *very hard* to use respectively. This informed the researcher that whereas the VCI, ADRICS and MoWT Rating methods were somewhat easy to use, some of the participants found these condition assessment methods fair to hard, necessitating an improved pavement condition assessment method.

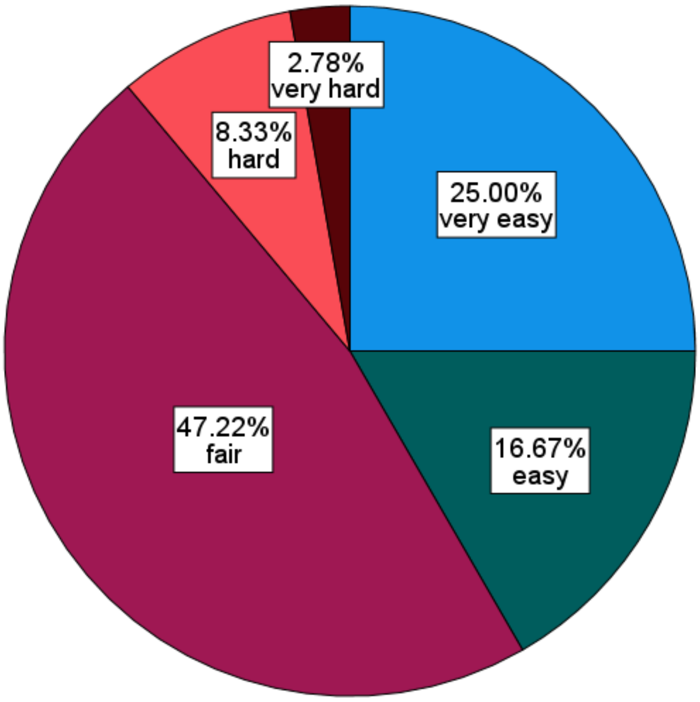


Figure 5.6: Ease of using the unpaved condition assessment method used by the organization

Results from the survey also brought to light the frequency with which road agencies carryout pavement condition assessments for unpaved roads *(see Figure 5.7)*. 16.67% of the participants stated that they collected pavement condition data monthly, 11.11% quarterly, 58.33% annually, 2.78% biannually and 11.11% stated that data collection was infrequent. These results informed the researcher that while the majority of participants collected pavement condition data annually, this frequency was not appropriate for unpaved roads considering the fact that the condition of an unpaved road can literally change over-night when subjected to extreme weather changes or an unexpected increase in traffic loads.

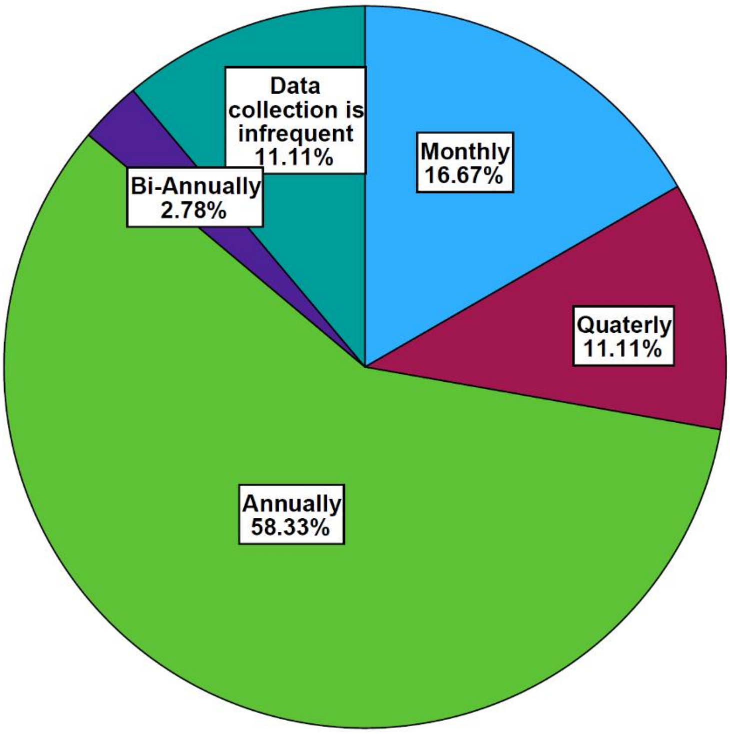


Figure 5.7: Frequency of carrying out pavement condition assessments for unpaved roads

Participants were also requested to answer the following question regarding the pavement condition assessment method being used by their organization; *"Can the condition rating derived from your pavement condition assessment be used to predict future pavement deterioration of unpaved roads?".* Results from the participants indicated that 52.78% answered *"No"* while 47.22% answered *"Yes"*. These results informed the researcher that the majority of the participants could not use the condition rating derived from their pavement condition assessment method to predict future pavement deterioration of unpaved roads. This implied that the new method's ability to predict future pavement deterioration from the condition rating derived from the novel Gravel Road Condition Index (GRCI) would be of significant importance in aiding road maintenance engineers plan future maintenance interventions for the unpaved road network.

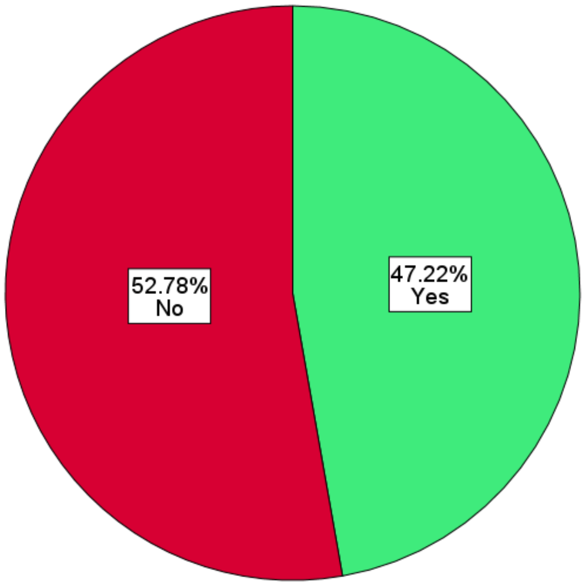


Figure 5.8: Participants response to the question; "Can the condition rating derived from your pavement condition assessment be used to predict future pavement deterioration of unpaved roads?"

5.5 Results from Participants on the high impact road surface distresses for unpaved roads

The crux of the survey was to establish the high impact road surface distresses for unpaved roads in Uganda. The questionnaire issued to participants included nine (09) road surface distresses that were identified after carrying out a comprehensive literature review as elaborated in subsection 2.5. The nine (09) road surface distresses were; 1) inadequate drainage, 2) inadequate gravel thickness, 3) camber loss, 4) corrugations, 5) loose gravel, 6) stoniness, 7) potholes, 8) erosion gullies, and 9) rutting. Participants were required to establish the road surface distresses that have the highest impact on the condition rating of unpaved roads in Uganda using the 5-point Likert Scale described in subsection 4.8.3.

5.5.1 Data Analysis Tools

The quantitative data obtained from the survey was first manually entered in Microsoft Excel 365 spreadsheets. The data entered was then cross-checked to ensure that there were no errors prior to data analysis. It should be noted that of the 36 (out of 70) questionnaires returned by the participants, all of them had been fully answered with none having any missing information. The Microsoft Excel 365 screened data was then exported to IBM SPSS Statistics version 27 (Statistical Package for the Social Sciences) for analysis and statistical testing of the various variables identified by this researcher.

5.5.2 Survey Results

Results from Part B of the questionnaire establishing the road surface distresses that have the highest impact on the condition rating of unpaved roads in Uganda are summarized in Table 5.1 below.

Table 5.1: Summary of survey results to establish the road surface distresses that have the highest impact on the condition rating of unpaved roads in Uganda

S/N	Distresses	Impact Rating					Total Responses (N)	Total Score	Std. Deviation (SD)	Mean Value	Weight Factor	Rank
		1	2	3	4	5						
1	Inadequate drainage	1	0	2	6	27	36	166	0.838	4.61	**0.137**	1
2	Inadequate gravel thickness	1	1	17	11	6	36	128	0.909	3.56	**0.106**	6
3	Camber loss	0	5	10	13	8	36	132	0.986	3.67	**0.109**	5
4	Corrugations	3	3	15	11	4	36	118	1.059	3.28	**0.098**	8
5	Loose gravel	1	2	17	8	8	36	128	0.998	3.56	**0.106**	7
6	Stoniness	2	6	21	4	3	36	108	0.926	3.00	**0.089**	9
7	Potholes	1	2	7	9	17	36	147	1.079	4.08	**0.121**	3
8	Erosion gullies	1	2	4	13	16	36	149	1.018	4.14	**0.123**	2
9	Rutting	1	3	8	17	7	36	134	0.974	3.72	**0.111**	4

Table 5.1 summarizes the responses from the 36 participants. The nine (09) road surface distresses were rated according to their impact on the condition rating of unpaved roads. The results showed that *"Inadequate drainage"* was ranked 1st with a

mean value of 4.61 which meant that this road surface distress had the most severe impact on the condition rating. *"Erosion gullies"* were ranked 2nd with a mean value of 4.14 while *"Potholes"* came in 3rd with a mean value of 4.08.

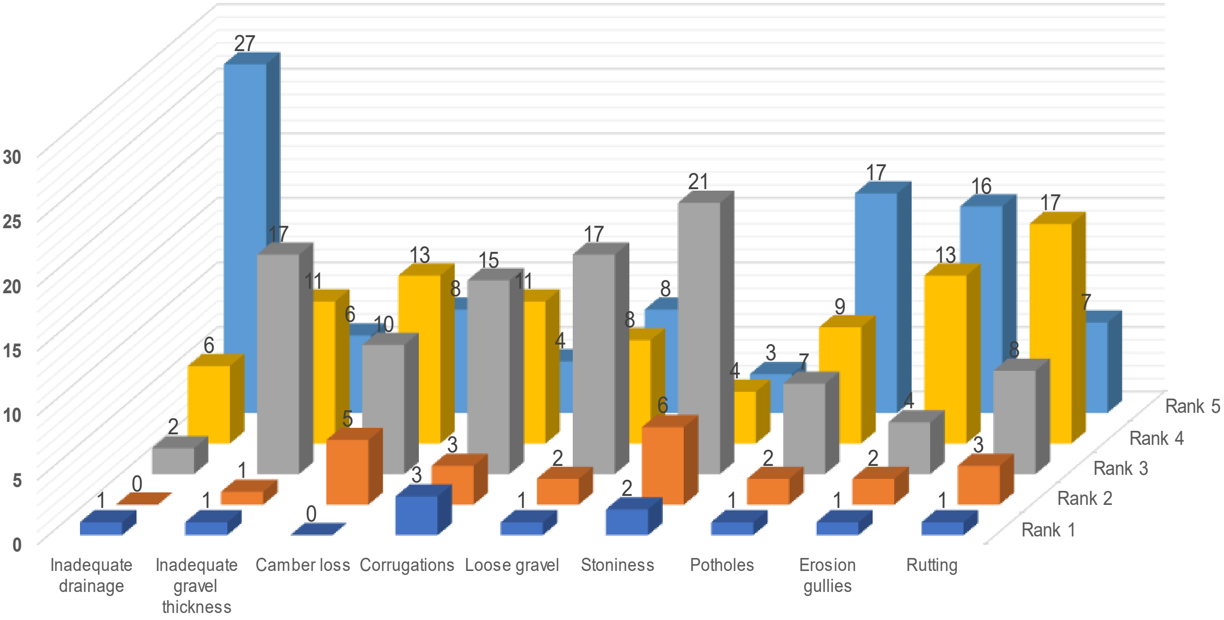


Figure 5.9: Participant's individual ranking of the nine (09) distresses

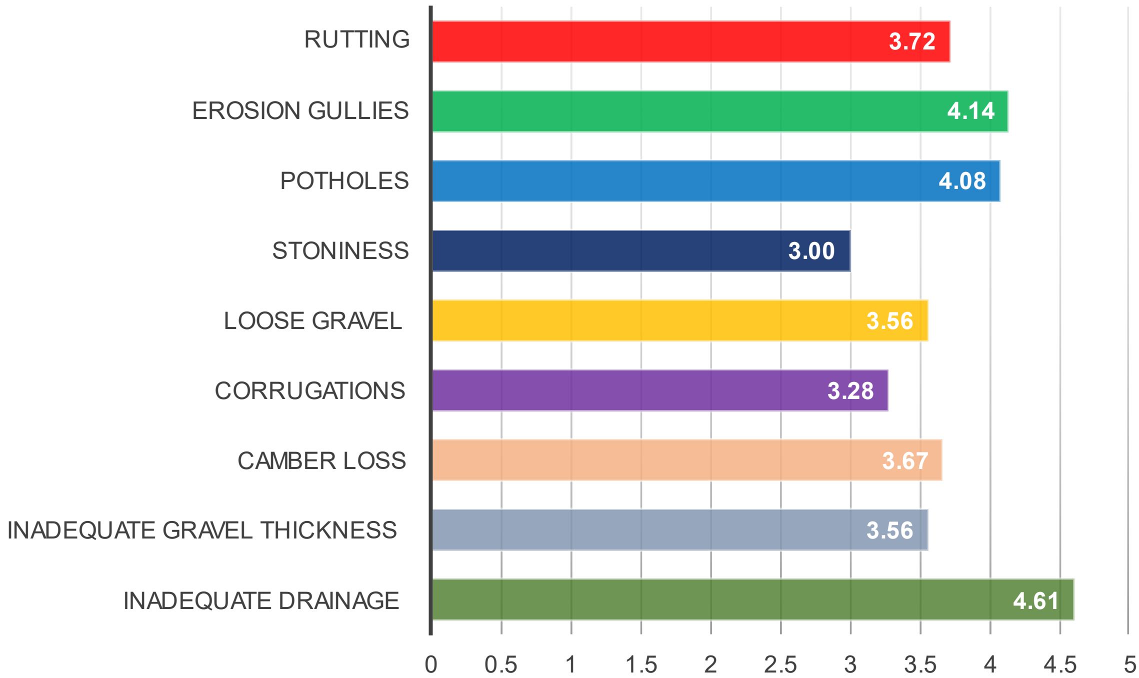


Figure 5.10: Individual mean values of each road surface distress

"Rutting", *"Camber loss"* and *"Inadequate gravel thickness"* were ranked 4^{th}, $5^{th,}$ and 6^{th} with mean values of 3.72, 3.67 and 3.56 respectively. Further still, *"Loose gravel"*, *"Corrugations"* and *"Stoniness"* were ranked 7^{th}, $8^{th,}$ and 9^{th} with mean values of 3.56, 3.28 and 3.00 respectively. The total score for each of the distresses was obtained by multiplying the impact rating score by the number of participants that scored that individual distress. For example, the total score of Inadequate drainage of 166 was obtained by (1x1)+(0x2)+(2x3)+(6x4)+(27x5)=166. The Standard Deviation (SD) value, which is a measure of how the data is spread across the mean, presented values of between 1.079 (Maximum SD) to 0.838 (Minimum SD). The SD values informed the researcher that the ratio of the maximum to the minimum standard deviation was approximately 1.3:1 which was within the 2:1 ratio suggested by Rahman Othman et al. (2011) for standard deviations within a Likert scale.

5.5.3 Weight Factors

One of the most important outcomes of the survey was to use the distress mean values to obtain weight factors for each of the road surface distresses in order to enable the development of the Gravel Road Condition Index (GRCI). According to Odu (2019), the *"mean weight method"* is an objective weighting method that employs mean values to obtain weight factors. This researcher made use of this method to determine the weight factors of the nine (09) road surface distresses which range from 0.137 to 0.089 as summarized in Table 5.2 below.

Table 5.2: Weight Factors for each road surface distress

S/N	Distresses	Weight Factor
1	Inadequate drainage	**0.137**
2	Inadequate gravel thickness	**0.106**
3	Camber loss	**0.109**
4	Corrugations	**0.098**
5	Loose gravel	**0.106**
6	Stoniness	**0.089**
7	Potholes	**0.121**
8	Erosion gullies	**0.123**
9	Rutting	**0.111**

5.6 Reliability analysis of the survey results

Taherdoost (2018), Garth (2008), Aithal and Aithal (2020) all agree that a Cronbach's Alpha coefficient of 0.70 or higher is considered *"acceptable"* and indicates adequate internal consistency of the questionnaire. This researcher after analyzing for reliability using IBM SPSS Statistics version 27 obtained an overall Cronbach's Alpha coefficient of 0.845 which indicated high internal consistency and reliability of the research questionnaire.

Table 5.3: Results from the reliability analysis using Cronbach's Alpha

S/N	Distresses	Cronbach's Alpha if Item Deleted	Cronbach's Alpha for the 9 items
1	Inadequate drainage	0.835	**0.845**
2	Inadequate gravel thickness	0.841	
3	Camber loss	0.835	
4	Corrugations	0.816	
5	Loose gravel	0.828	
6	Stoniness	0.843	
7	Potholes	0.820	
8	Erosion gullies	0.824	
9	Rutting	0.815	

5.7 Summary of Chapter

The survey results for the high impacting road surface distresses have been discussed in this chapter. 36 out of 70 issued questionnaires were returned by the participants which represented a response rate of 51.4%. The questionnaire targeted a very specific group of engineering professionals i.e., road maintenance engineers and road inspectors who are few in number and spread across the various districts in the Country.

Of the nine (09) distresses identified from the literature review i.e., Inadequate drainage, Inadequate gravel thickness, Camber loss, Corrugations, Loose gravel, Stoniness, Potholes, Erosion gullies and Rutting, results from the survey indicated that inadequate drainage had the most severe impact on the condition rating and had the highest weight factor of 0.137.

Having identified the high impacting road surface distresses that affect the condition rating of unpaved roads in Uganda and ranked them with their corresponding weight factors, the next stage of the study was to use these weight factors to develop the Gravel Road Condition Index (GRCI).

Chapter Six

DEVELOPMENT OF THE GRAVEL ROAD CONDITION INDEX (GRCI)

6.1 Introduction to development of condition indices

The findings from the literature review and questionnaire survey exposed the need for an improved condition assessment method for unpaved roads in Uganda. A review of the results from chapter five revealed that development of an overall condition index could be obtained as a function of the weighting factor and severity combination for the nine (09) identified distresses. Garcia (2000) suggests that pavement distresses maybe combined into a single index that can be used to measure the functional performance of a pavement. This novel index, termed the Gravel Road Condition Index (GRCI), was developed through deploying a mathematical model that takes into account the weighting factors of each individual road surface distress. These weighting factors were determined through making use of the *Analytic Hierarchy Process* (AHP) to convert the subjective survey results into objective mathematical data.

Pavement performance indices can be developed through various methods which include: *(1)* using deduct values, *(2)* using weighted sums, *(3)* using fuzzy set theory, *(4)* using Artificial Neural Networks (ANN) and *(5)* using direct panel ratings (Garcia, 2000: Fatih Bektas et al., 2014). This research study deployed the weighted sums method in developing the GRCI owing to the fact that AHP has been used in determining the individual weight factors of each distress.

This chapter will therefore discuss the development of the GRCI model, examine distress weighting using the AHP method and describe the condition rating system applicable to the model. The structure and application of the GRCI model in the Ugandan context for unpaved roads is also detailed in the succeeding passages.

6.2 Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) is a measurement theory that employs pairwise comparisons and depends on the judgements of experts to derive priority scales (Saaty, 2008). This Multi-Criteria Decision Making (MCDM) method that was originally developed in the 1970's by Prof. Thomas L. Saaty at the University of Pittsburgh can be used to determine the relative weight of each factor influencing the decision results (Musfiqur et al., 2020). Simply put, AHP is a theory and methodology for relative mathematical measurement (Brunelli, 2015).

According to Mardani et al. (2015), AHP was the most used MCDM method in the field of construction. In contrast, Eltarabishi et al. (2020) asserted that while the AHP method was ranked 1st from 2000 to 2014, the trend had changed with the AHP method ranking 2nd between 2014 to 2019. This research study adopted the AHP method because it facilitated a simple and comprehensive evaluation of the nine (09) attributes by incorporating both qualitative and quantitative factors. Additionally, the AHP method also provided a consistent framework for the use of pairwise comparison matrices which reduced biases and ensured transparency (Sahoo and Goswami, 2023).

AHP has been used by pavement performance researchers to develop mathematical models for road condition assessments. This researcher found that pavement performance researchers deployed the AHP method instead of other MCDM methods because of AHP's ease of use and ability to accommodate a large number of elements. Salman et al. (2021) utilized AHP to develop a condition assessment model for a residential road network in Dammam City (Saudi Arabia). A comparison matrix was used to calculate the relative weight factors obtained from the local priorities of each road pavement distress. The results of the Salman et al. (2021) study indicated that an efficient condition assessment model could be developed using AHP.

Similarly, Ahmed et al. (2017) applied the AHP method in the prioritization of pavement maintenance sections in Mumbai City (India). The study compared the results of the pairwise priority ratings of the AHP method with the results from the existing road condition index and found that the AHP method was more suitable for the prioritization of pavement maintenance of roads in Mumbai City. The Ahmed et al. (2017) study further reinforced the fact that the AHP method provides a more accurate priority ranking criteria.

Research done by Alfar (2016) analysed the responses from a questionnaire survey using the AHP pairwise comparison methodology to determine the maintenance priority of the roads in Surrey County (UK). The Alfar (2016) study is relevant to this research study because it established a link between the subjective data obtained from a questionnaire survey and AHP pairwise comparison matrices. This research study has therefore also made use of the information obtained from the questionnaire survey in chapter five to develop AHP pairwise comparison matrices for the (09) identified distresses. It is important to note that AHP pairwise comparison matrices are made using a scale of relative importance *(fundamental scale for pairwise comparisons)* as shown in Table 6.1.

Table 6.1: Scale of relative importance (fundamental scale for pairwise comparisons) (Saaty, 2008)

Intensity of importance	**Definition**	**Explanation**
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment moderately favor one element over another
5	Strong importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another, its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgements	Where compromise is needed
Reciprocals of the above	Values for inverse comparison: 1/2, 1/3, 1/4, 1/5, 1/6, 1/7, 1/8, 1/9	

AHP pairwise comparison matrices make use of the 1 to 9 scale of importance shown in Table 6.1 to compare how much more one element dominates the other regarding a given attribute. These pairwise matrices can convert the subjective judgements of experts into numerical values where 1 means that two elements are of equal importance and 9 means an extreme importance of one element over another (Gompf et al., 2021).

This researcher will demonstrate in the succeeding section 6.3 how the AHP method was used to establish the weighting factors for each of the nine (09) identified distresses from the questionnaire survey.

6.3 Distress weighting using the AHP method

As discussed in section 6.2, the AHP method has been used by this researcher to establish alternative distress weighting factors from the subjective judgements of experts (i.e., road maintenance industry practitioners) obtained from the questionnaire survey.

Table 6.2: Summary of results from the questionnaire survey

Distresses	Impact Rating					Total Responses (N)	Total Score	Weight Factor	Rank
	1	2	3	4	5				
Inadequate drainage	1	0	2	6	27	36	**166**	0.137	**1**
Inadequate gravel thickness	1	1	17	11	6	36	**128**	0.106	**6**
Camber loss	0	5	10	13	8	36	**132**	0.109	**5**
Corrugations	3	3	15	11	4	36	**118**	0.098	**8**
Loose gravel	1	2	17	8	8	36	**128**	0.106	**7**
Stoniness	2	6	21	4	3	36	**108**	0.089	**9**
Potholes	1	2	7	9	17	36	**147**	0.121	**3**
Erosion gullies	1	2	4	13	16	36	**149**	0.123	**2**
Rutting	1	3	8	17	7	36	**134**	0.111	**4**

The subjective results from the questionnaire survey in chapter five are summarized in Table 6.2. This summary indicated the total score of each distress from the 36 participants of the survey and showed the ranking of the distresses in-terms of having the highest impact on the condition rating of unpaved roads in Uganda.

The mean weight factors of the distresses are also shown in the above summary table and were obtained through applying the *“mean weight method”* in descriptive statistics. This method employs mean values to obtain weight factors as discussed in subsection 5.5.3 of this thesis. This researcher, however, noted that the weight factor values shown in Table 6.2 were not appropriate for the development of the GRCI model. This was because the weight factor values from the survey were normally distributed (i.e., between 9% to 14%) and no comparison was made to ascertain the impact of one distress over another on the condition rating of unpaved roads in Uganda. The AHP method was in contrast found to be appropriate because it could carry out relative mathematical measurement.

Distress weighting using the AHP method was obtained by performing the following steps as proposed by Saaty (2008), Alfar (2016), Masoumi et al. (2017), and Vaidya & Kumar (2006);

1. Define the goal and develop the AHP hierarchy.
2. Construct a pairwise comparison matrix.
3. Normalize the matrix by establishing the weighing.
4. Test for consistency.

6.3.1 Define the goal and develop the AHP hierarchy

The first step was to define the goal of the AHP. This researcher noted that the goal of the AHP was to establish the weight factors for each of the road surface distresses affecting the condition rating of unpaved roads in Uganda. Masoumi et al. (2017) assert that the AHP hierarchy structure can be represented as a simple decision tree diagram in which the goal is located at the highest level with the attributes and alternatives located below the goal as shown in Figure 6.1.

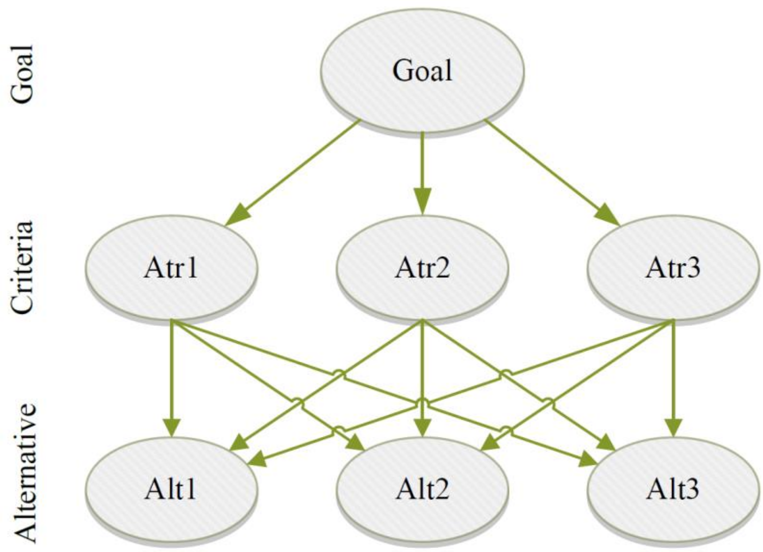


Figure 6.1: AHP Hierarchy Structure (Masoumi et al., 2017)

It is however important to note that the AHP hierarchy structure applicable to this study only had two levels i.e., the goal and the attributes or elements. The AHP method in this study was used to determine the weight factors of the road surface distresses and as such there was no need for formulating the decision alternatives.

6.3.2 Construct a pairwise comparison matrix

The next step of the AHP method involved constructing a pairwise comparison matrix which was done using the matrix equation proposed by Saaty (2008) as shown in eq.6.1. The rows and columns in eq.6.1 consist of attributes that are compared against each other using Saaty's 9-point scale of importance to obtain the attribute judgement values (see Table 6.4).

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \qquad \textbf{\textit{(eq.6.1)}}$$

Where; $\boldsymbol{a}$ = attribute and $\boldsymbol{n}$ = number of attributes

Table 6.3: AHP pairwise comparison matrix for the road surface distresses

	Inadequate drainage	Inadequate gravel thickness	Camber loss	Corrugations	Loose gravel	Stoniness	Potholes	Erosion gullies	Rutting
	D1	D2	D3	D4	D5	D6	D7	D8	D9
D1	1.000	5.000	4.000	6.000	5.000	7.000	3.000	3.000	4.000
D2	0.200	1.000	0.500	2.000	1.000	3.000	0.333	0.333	0.500
D3	0.250	2.000	1.000	3.000	2.000	3.000	0.333	0.333	0.500
D4	0.167	0.500	0.333	1.000	0.500	2.000	0.250	0.250	0.333
D5	0.200	1.000	0.500	2.000	1.000	3.000	0.333	0.333	0.500
D6	0.143	0.333	0.333	0.500	0.333	1.000	0.200	0.167	0.333
D7	0.333	3.000	3.000	4.000	3.000	5.000	1.000	0.500	2.000
D8	0.333	3.000	3.000	4.000	3.000	6.000	2.000	1.000	3.000
D9	0.250	2.000	2.000	3.000	2.000	6.000	0.500	0.333	1.000

The AHP pairwise comparison matrix shown in Table 6.3 was developed by this researcher for the nine (09) road surface distresses and were denoted D1 to D9. The 9-by-9 matrix values were populated in MS Excel spreadsheets based on the total score of each distress obtained from the subjective questionnaire survey. This researcher made pairwise comparisons of two distresses at a time, for example, inadequate drainage (D1) verses stoniness (D6) and determined a scale of 7 or 1/7 (the reciprocal value) which meant that inadequate drainage was '*very strongly more important'* than stoniness. In this example, the Saaty-scale values of 7.000 or 0.143 (the reciprocal) represented the relative superiority of the two distresses against one another.

Table 6.4: Calculation of the Saaty-scale values for inadequate drainage (D1) verses stoniness (D6)

Distress		Total Score	Variance	AHP scale
Inadequate drainage	**D1**	**166**	**-58**	**0.143**
Inadequate gravel thickness	D2	128	-20	0.333
Camber loss	D3	132	-24	0.333
Corrugations	D4	118	-10	0.500
Loose gravel	D5	128	-20	0.333
Stoniness	**D6**	**108**		
Potholes	D7	147	-39	0.200
Erosion gullies	D8	149	-41	0.167
Rutting	D9	134	-26	0.333

For the D1 verses D6 example stated above, the AHP scale or attribute judgement value for inadequate drainage (D1) verses stoniness (D6) was calculated from the variance between the total scores of the distresses obtained from the questionnaire survey.

6.3.3 Normalise the matrix by establishing the weighing

Step 3 of the AHP method was to normalise the matrix by calculating the column totals of the Saaty-scale judgment values of each distress in the pairwise comparison matrix. Each judgment value in the pairwise matrix was then divided by the column total *(i.e., all the elements of the column were divided by the sum of that column)* to produce a normalised matrix as shown in Table 6.5 below.

Table 6.5: Normalised matrix for the road surface distresses

	Inadequate drainage	Inadequate gravel thickness	Camber loss	Corrugations	Loose gravel	Stoniness	Potholes	Erosion gullies	Rutting		
	D1	D2	D3	D4	D5	D6	D7	D8	D9	**Weight *(W)***	**Ranking**
D1	0.348	0.280	0.273	0.235	0.280	0.194	0.377	0.480	0.329	**0.311**	**1**
D2	0.070	0.056	0.034	0.078	0.056	0.083	0.042	0.053	0.041	**0.057**	**6**
D3	0.087	0.112	0.068	0.118	0.112	0.083	0.042	0.053	0.041	**0.080**	**5**
D4	0.058	0.028	0.023	0.039	0.028	0.056	0.031	0.040	0.027	**0.037**	**8**
D5	0.070	0.056	0.034	0.078	0.056	0.083	0.042	0.053	0.041	**0.057**	**7**
D6	0.050	0.019	0.023	0.020	0.019	0.028	0.025	0.027	0.027	**0.026**	**9**
D7	0.116	0.168	0.205	0.157	0.168	0.139	0.126	0.080	0.164	**0.147**	**3**
D8	0.116	0.168	0.205	0.157	0.168	0.167	0.252	0.160	0.247	**0.182**	**2**
D9	0.087	0.112	0.136	0.118	0.112	0.167	0.063	0.053	0.082	**0.103**	**4**
	1.000	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**	

The weight *(W)* of each road surface distress was then calculated by obtaining the arithmetic mean of each row in the normalised matrix. The derived weights were: w1 = 0.311, w2 = 0.057, w3 = 0.080, w4 = 0.037, w5 = 0.057, w6 = 0.026, w7 = 0.147, w8 = 0.182 and w9 = 0.103.

Table 6.6: Comparison between the AHP method and Statistics method

Distresses	AHP Method			Statistics Method		
	Weight Factor *(W)*	**% Weight**	**Rank**	**Weight Factor *(W)***	**% Weight**	**Rank**
Inadequate drainage	0.311	31%	1	0.137	14%	1
Inadequate gravel thickness	0.057	6%	6	0.106	11%	6
Camber loss	0.080	8%	5	0.109	11%	5
Corrugations	0.037	4%	8	0.098	10%	8
Loose gravel	0.057	6%	7	0.106	11%	7
Stoniness	0.026	3%	9	0.089	9%	9
Potholes	0.147	15%	3	0.121	12%	3
Erosion gullies	0.182	18%	2	0.123	12%	2
Rutting	0.103	10%	4	0.111	11%	4

This researcher also carried out a comparison between results obtained from the AHP method and those from the Statistics method noting that the weight factors varied significantly between both methods. It was also revealed that the priority ranking was the same for both methods. The AHP method, however, provided values that more realistically represented the weight factors of road surface distresses in Uganda. A comparison analysis between the weight factors obtained from this research study using the AHP method and the existing weight factors currently in use on Ugandan unpaved roads will be subsequently discussed in chapter seven.

6.3.4 Test for consistency

Having obtained the weight factors of each road surface distress from the normalised matrix, the last step of the AHP method was to test for consistency. According to Franek and Kresta (2014), the consistency of a matrix could be tested by first determining the largest Eigen value, λ_{max}, from the following eq.6.2;

$$\lambda_{max} = \sum_{j=1}^{m} \frac{(S.V)j}{m\,.v_j} \qquad \textbf{\textit{(eq.6.2)}}$$

Where; m = the number of rows in the normalised matrix

S = the pair-wise comparison matrix

v = the matrix eigenvector

The largest Eigen value (λ_{max}) was then used to derive the Consistency Index (CI) as shown in Table 6.7 below.

Table 6.7: Consistency Test Calculations

	D1	D2	D3	D4	D5	D6	D7	D8	D9	**Wieghted Sum Value**	**Weight *(W)***	**Ratio**
D1	0.311	0.285	0.319	0.220	0.285	0.184	0.441	0.546	0.413	3.005	0.3108	9.669
D2	0.062	0.057	0.040	0.073	0.057	0.079	0.049	0.061	0.052	0.530	0.0571	9.278
D3	0.078	0.114	0.080	0.110	0.114	0.079	0.049	0.061	0.052	0.736	0.0796	9.242
D4	0.052	0.029	0.027	0.037	0.029	0.053	0.037	0.046	0.034	0.341	0.0367	9.301
D5	0.062	0.057	0.040	0.073	0.057	0.079	0.049	0.061	0.052	0.530	0.0571	9.278
D6	0.044	0.019	0.027	0.018	0.019	0.026	0.029	0.030	0.034	0.248	0.0263	9.435
D7	0.104	0.171	0.239	0.147	0.171	0.131	0.147	0.091	0.207	1.408	0.1470	9.580
D8	0.104	0.171	0.239	0.147	0.171	0.158	0.294	0.182	0.310	1.776	0.1821	9.753
D9	0.078	0.114	0.159	0.110	0.114	0.158	0.073	0.061	0.103	0.971	0.1034	9.390
											λ max =	**9.436**
											CI =	0.055
											RI =	1.45
											CR =	**0.0376**

This researcher also made use of MATLAB computation software to compare the Eigen value. The MS Excel calculation resulted into a λ_{max} value of 9.4361 while the MATLAB software computed a value of 9.4347. Since the values obtained from both computational approaches were comparable, this researcher was therefore able to ascertain the validity of the of the largest Eigen value (λ_{max}).

The Consistency Index (CI) was then derived from the Eigen value (λ_{max}) using the following eq.6.3 as proposed by Saaty (2008). A CI value of 0.055 was obtained.

$$CI = \frac{\lambda_{max} - n}{n - 1} \qquad \boldsymbol{(eq.6.3)}$$

Where; n = the number of elements or attributes

λ_{max} = the largest Eigen value

Having obtained the Consistency Index (CI), the next step was to determine the Consistency Ratio (CR). Saaty (2008) describes CR as the degree of compatibility for data analysed by the AHP method. The Consistency Ratio reveals any potential incompatibility by establishing whether the inconsistency in the pairwise comparison matrix is acceptable or not (Alfar, 2016: Musfiqur et al., 2020). If the CR ≤ 0.1, then the inconsistency would be deemed acceptable, however, a CR of greater than 0.1 would imply that the pairwise comparison matrix should be re-examined in-order to obtain better consistency (Musfiqur et al., 2020). The Consistency Ratio (CR) was as shown in eq.6.4.

$$CR = \frac{CI}{RI} \qquad \boldsymbol{(eq.6.4)}$$

Where; *CI* = the Consistency Index

RI = the Random Index

The Random Index (RI) value was extracted from the is Random Inconsistency Index table developed by Saaty (1980) for fifteen (15) elements with different matrix orders as shown in Table 6.8 (Alfar, 2016).

Table 6.8: Random inconsistency index (Alfar, 2016)

N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

Since this study established nine (09) matrix orders for the nine (09) road surface distresses, a corresponding RI value of 1.45 was used to calculate the Consistency Ratio (CR). By applying eq.6.4, the CR was calculated as follows;

CR = CI / RI, CR = 0.055 / 1.45 = 0.0376

Since the CR value of 0.0376 was less than 0.1, this researcher established that the weighting factors derived from the AHP method were acceptable and that the pairwise comparison matrix had passed the consistency test.

6.4 Distress severity rating procedure

The distress severity rating was another important parameter in the development of the novel GRCI model. Having derived the weighting factors of each road surface distress from the AHP method, it was also important to ascertain the distress severity rating procedure applicable to the GRCI model. Mbabazi (2019) suggests that a 1 to 5 scale could be used to rate the severity of road distresses on unpaved roads in Uganda.

Table 6.9: Distress rating criteria (Mbabazi, 2019)

Distress rating	**1**	**2**	**3**	**4**	**5**
Severity description	Slight	Slight to warning	Warning	Warning to severe	Severe

The distress rating criteria shown in Table 6.9 was deployed to assess the severity of various distresses whose values were used as inputs to compute the functional index of unpaved roads in eastern Uganda (Mbabazi, 2019). The South African Standard Visual Assessment Manual for Unsealed Roads (TMH12) also rates unpaved road distresses according to a 5-point severity scale (CSIR, 2000). This researcher therefore adopted a 5-point severity scale in the GRCI model based on the ease of use and the scale's ability to adequately communicate the degree of distress severity.

Table 6.10: The 5-point severity scale for the GRCI model

DISTRESS SEVERITY	
Value	**Description**
1	**No Occurrence**
2	Better than Average
3	**Average Occurrence**
4	Worse than Average
5	**Excessive Occurrence**

Table 6.11: The detailed distress severity classification

D1	Inadequate drainage
Value	**Detailed Description**
1	Clear; no visible obstacles; siltation, debris, well functioning drainage for respective side of the section.
2	Generally clear with a few obstacle; siltation, debris, functioning drainage for respective side of the section.
3	Slightly overgrown with some obstacles; siltation, debris or erosion in drainage of respective side of the road.
4	Partly blocked; depth of drainage less than designed due to siltation; debris, or some erosion occurs on respective side of the section.
5	Blocked; eroded or non-existent and not functioning as drainage.

D2	Inadequate gravel thickness
Value	**Detailed Description**
1	Consistent gravel surface with a good profile and no stone protrusion.
2	Gravel loss can be seen but still good shape and only limited stone protrusion.
3	Medium gravel loss can be seen but no exposure of the sub-grade; or Sub-grade exposed in local areas.
4	Severe exposure of sub-grade; or Engineered cross section on road non existing on part of the section.
5	No gravel found on the section; 100% of sub-grade exposed; Engineered cross section on road non existing.

D3	Camber loss
Value	**Detailed Description**
1	Ride very smooth and very comfortable; No unevenness of the transverse profile; No rutting or potholes.
2	Ride smooth/fair and comfortable; Moderate unevenness of the transverse profile; Moderate rutting but no potholes.
3	Ride poor and uncomfortable; Frequent unevenness of the transverse profile; Significant rutting, corrugations and occasional potholes.
4	Ride very poor and very uncomfortable; Severe unevenness of the transverse profile; Extensive rutting, corrugations and several potholes; Road unsafe owing severe unevenness.
5	Impassable except by 4 Wheel Drive vehicles.

D4	Corrugations
Value	**Detailed Description**
1	No corrugations.
2	Can be felt and heard; no speed reduction necessary.
3	Can be felt and heard; speed reduction necessary.
4	Significant speed reduction necessary.
5	Drivers select a different path and drive very slowly; Road safety is affected.

D5	Loose gravel
Value	**Detailed Description**
1	No visible loose material.
2	Slightly visible loose material; Speed reduction not necessary.
3	Visible loose material; Speed reduction necessary.
4	Significantly visible loose material; Significant speed reduction necessary.
5	Excessive loose material; Vehicles drive very slowly in section with loose material; Road safety is affected.

D6	Stoniness
Value	**Detailed Description**
1	No visible protruding stones.
2	Slightly visible protruding stones.
3	Visible protruding stones; Speed reduction necessary.
4	Significantly visible protruding stones; Significant speed reduction necessary.
5	Excessive occurrence of protruding stones; Vehicles drive very slowly to avoid protruding stones.

D7	Potholes
Value	**Detailed Description**
1	No potholes.
2	Slight emergence pf potholes; Speed reduction not necessary.
3	Potholes have started to effect travelling speed.
4	Potholes significantly effect travelling speed.
5	Excessive occurrence of Potholes; Vehicles drive very slowly in section with potholes.

D8	Erosion gullies
Value	**Detailed Description**
1	No erosion gullies.
2	Slightly visible erosion gullies.
3	Ruts show clear signs of erosion (gullies); Occasional diversion of longitudinal flow to side drains or terrain.
4	Minor erosion gullies meander from rut to rut and occasionally from ditch to ditch.
5	Ruts show heavy erosion (gullies); Major erosion gullies have developed along ditches. Road safety is affected.

D9	Rutting
Value	**Detailed Description**
1	No rutting.
2	Limited rutting.
3	Rutting discernible (visible).
4	Obvious rutting.
5	Severe rutting, dangerous and affects directional stability.

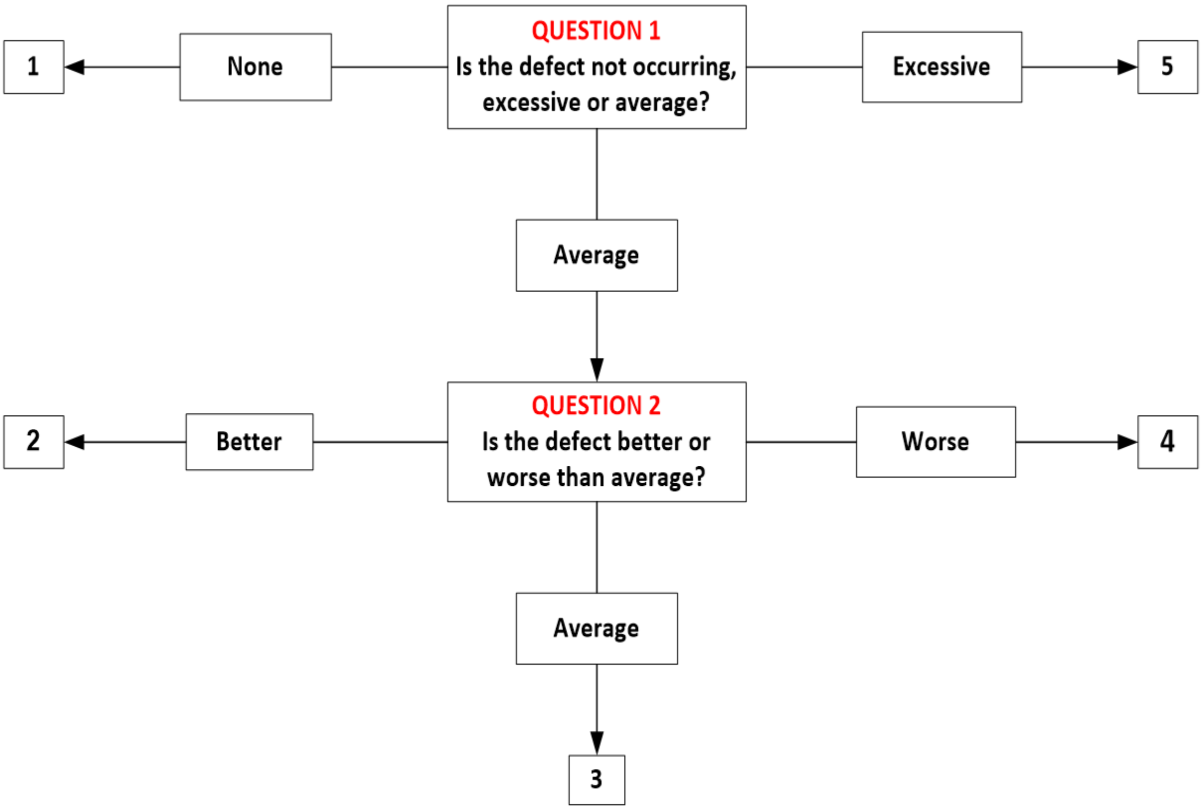


Figure 6.2: The 5-point distress severity rating procedure (CSIR, 2000)

Table 6.10 shows the 5-point severity scale employed for the GRCI model. The detailed distress severity classification shown in Table 6.11 can be used by road assessors to identify the distress severity values. The rating procedure illustrated in Figure 6.2 indicates the flow through which an assessor could ascertain the severity scale value for each of the nine (09) identified distresses. The most important scale values are 1, 3 and 5. In the event the assessor is uncertain of the severity between 1 and 3 or 3 and 5, the distress severity value of 2 or 4 could be applied respectively.

6.5 Condition rating system

Developing the Gravel Road Condition Index (GRCI) also required establishing a robust condition rating system. Typical condition rating systems for unpaved roads include a point rating system for each road surface distress with weight factors applied to each distress to generate a total rating for a road section (FCM, 2003). This researcher had identified a number of condition rating systems that were applicable to unpaved roads and as such relevant in the development of the GRCI rating system.

The South African Standard Visual Assessment Manual for Unsealed Roads (TMH12) classified unpaved road sections into one of five condition categories i.e. *(1)* very good, *(2)* good, *(3)* fair, *(4)* poor and *(5)* very poor (CSIR, 2000). This South African condition rating system was the same as the 1 to 5 rating provided in the Australian Best Practice Guide for Unsealed Roads as indicated in Table 6.12. The American Gravel PASER discussed in section 2.7 also deployed a simplified condition rating system with a scale of 1 (Failed) to 5 (Excellent) for gravel roads.

Table 6.12: South African and Australian unpaved road condition rating system (CSIR, 2000)

Condition categories	**1**	**2**	**3**	**4**	**5**
	Very Good	Good	Fair	Poor	Very Poor

This researcher also established that the 1 to 5 scale was applied by road agencies in Uganda because five condition values were described in the Ugandan Road Maintenance Management Manual (MoWT, 2010). Additionally, research done by Mbabazi (2019) on the impact of unpaved road condition on rural transport services in eastern Uganda made use of a qualitative condition rating system with five (05) condition categories. This researcher therefore used the 1 to 5 condition rating system for classifying the condition of unpaved roads in Uganda.

Table 6.13: The 1 to 5 condition rating system for the GRCI model

GRCI Classification	
Value	**Condition Category**
1	Excellent
2	Good
3	Fair
4	Poor
5	Failed

The GRCI condition rating system classified the condition of unpaved roads into five (05) categories i.e. *(1)* Excellent, *(2)* Good, *(3)* Fair, *(4)* Poor and *(5)* Failed. It should, however, be noted that the GRCI rating system reversed the 1 (Very Poor) to 5 (Excellent) scale indicated in the Ugandan Road Maintenance Management Manual. This reversed rating system originated from the fact that a 5-point severity scale had been adopted with the severity value of 5 representing excessive occurrence of a distress.

6.6 The GRCI model

The Gravel Road Condition Index (GRCI) was developed as a mathematical model for the nine (09) identified distresses for unpaved roads in Uganda. The GRCI model took the form of a 5-point rating (values 1 to 5) and considered three (03) attributes of the distresses i.e.

- Type
- Severity and,
- Weight factor *(based on the AHP scale of relative importance)*

The GRCI was a function of the weighting factor and severity combination for the nine (09) identified distresses and applied the weighted sums method for developing condition indices. This researcher developed the GRCI based on the approach provided in the South African Standard Visual Assessment Manual for Unsealed Roads (TMH12). The approach calculated a condition index value for each section of assessed road length based on the combination of the severity rating and the weight factor of each distress type (CSIR, 2000).

This approach of combining pavement distresses into a single index that can be used to measure the functional performance of a pavement was utilized by Ndume et al. (2020) to develop an improved road condition index in Tanzania. Tawalare and Vasudeva Raju (2016) also developed a pavement performance index as a sum of the multiplication of rating and weightage of each deteriorating parameter for rural roads in India. Similarly, Attoh-Okine and Adarkwa (2013) noted that an overall pavement index could be developed by combining the weighting factor of each distress and the score or rating of the individual distress for roads in Pennsylvania (USA).

This researcher therefore developed a GRCI mathematical model based on the weighted sums method as shown in eq.6.5.

$$GRCI = \sum_{i=1}^{9} (W_i \ x \ S_i) \qquad (\boldsymbol{eq. 6.5})$$

Where; W_i = Weight of Distress

S_i = Distress Severity (Scale of 1 to 5)

i = Distress Type (1 to 9)

The general mathematical model shown in eq.6.5 was further expanded as represented in eq.6.6.

$$\mathrm{GRCI} = \mathrm{W_1S_1} + \mathrm{W_2S_2} + \mathrm{W_3S_3} + \ldots\ldots\ldots + \mathrm{W_9S_9} \qquad (eq. 6.6)$$

The Gravel Road Condition Index (GRCI) was therefore represented by the mathematical model shown in eq.6.7 for the nine (09) identified road surface distresses.

$$\mathbf{GRCI = 0.31S_1 + 0.06S_2 + 0.08S_3 + 0.04S_4 + 0.06S_5 + 0.02S_6 + 0.15S_7 + 0.18S_8 + 0.1S_9} \qquad (eq. 6.7)$$

Where; S_i = Distress Severity (Scale of 1 to 5)

6.7 Application of the GRCI

The Gravel Road Condition Index (GRCI) developed in section 6.6 could be used to;

- Determine the overall condition rating of an unpaved road network.
- Provide a condition rating of each section of assessed road length and,
- Classify a road section or road network into one of the five condition categories for statistical representation.

Since the GRCI combined identified pavement distresses into a single rating, comparisons can be made between road sections to facilitate prioritization of maintenance and rehabilitation activities. Additionally, the GRCI could be used to communicate the condition of a road network in a simplified way that can be easily understood by decision makers who include non-technical stakeholders such as politicians.

The GRCI of an unpaved road section can be determined by carrying out field-based condition assessments. These manual assessments are done using the condition assessment form developed by this researcher shown in Figure 6.3. The GRCI condition assessment form can be used by an assessor to record the severity value of each of the nine (09) identified distresses for a maximum of 1km per section. This is done through carrying out a visual windshield survey in an inspection vehicle traveling at a maximum of 20km/hr. The assessment form also records the road name, inspection date, assessors name and is used to calculate the GRCI rating that defines the condition category of the assessed road section.

Gravel Road Condition Index (GRCI)

Assessment Form

Road Name:____________________ **Date:**____________ **Form Code:**__________

Section (01 km-max):__________________ **Assessed by:**__________________

DISTRESS	DISTRESS WEIGHT (%)	DISTRESS SEVERITY (1 to 5)	STANDARDIZED VALUE (0.000)
Inadequate drainage	31		
Inadequate gravel thickness	6		
Camber loss	8		
Corrugations	4		
Loose gravel	6		
Stoniness	2		
Potholes	15		
Erosion gullies	18		
Rutting	10		
		Sum of Standardized Value =	
		GRCI =	

Condition Category

DISTRESS SEVERITY	
Value	**Description**
1	**No Occurrence**
2	Better than Average
3	**Average Occurrence**
4	Worse than Average
5	**Excessive Occurrence**

GRCI Classification	
Value	**Condition Category**
1	Excellent
2	Good
3	Fair
4	Poor
5	Failed

Section (01 km-max):__________________ **Assessed by:**__________________

DISTRESS	DISTRESS WEIGHT (%)	DISTRESS SEVERITY (1 to 5)	STANDARDIZED VALUE (0.000)
Inadequate drainage	31		
Inadequate gravel thickness	6		
Camber loss	8		
Corrugations	4		
Loose gravel	6		
Stoniness	2		
Potholes	15		
Erosion gullies	18		
Rutting	10		
		Sum of Standardized Value =	
		GRCI =	

Condition Category

DISTRESS SEVERITY	
Value	**Description**
1	**No Occurrence**
2	Better than Average
3	**Average Occurrence**
4	Worse than Average
5	**Excessive Occurrence**

GRCI Classification	
Value	**Condition Category**
1	Excellent
2	Good
3	Fair
4	Poor
5	Failed

Figure 6.3: The GRCI condition assessment form

The condition assessment is carried out by visually inspecting a 1km section, stopping and determining the GRCI rating of that section, before proceeding to assess the subsequent sections of an unpaved road. This researcher noted that because this manual condition assessment was subjective, repeatability for the GRCI ratings was of concern. It was however noted in the case study field-based validation assessment that the two assessors recorded the same overall rating indicating that the GRCI model had no repeatability concerns as discussed in subsection 7.4.4.

Application of the GRCI on an unpaved road of, 5kms for example, implies that the road is divided into 5 sections of 1km each and GRCI ratings determined for each of the 5 sections. The weighted average of the GRCI ratings of the 5 sections is the condition rating of the entire unpaved road.

6.8 Summary of Chapter

The development of the Gravel Road Condition Index (GRCI) was discussed in this chapter with emphasis placed on creating a mathematical model that made use of the Analytic Hierarchy Process (AHP) to convert the subjective survey results into objective weighting factors. The GRCI was derived as a function of the AHP weighting factors and severity combinations for the nine (09) identified distresses and applied the weighted sums method of developing condition indices.

Crucially, the developed GRCI can determine the overall condition rating of an unpaved road network, provide a condition rating of each section of assessed road length and classify a road section or road network into one of the five condition categories for statistical representation. This information is important because the GRCI communicates the condition of a road network in a simplified way that can be easily understood and interpreted by decision makers such as road maintenance engineers and politicians. The next chapter discusses validation of the GRCI through application of the method on a case-study gravel road and verifying the results through comparison with pre-existing condition assessment methods in Uganda. Furthermore, this researcher also, in the next chapter, details the relationship between the GRCI and the gravel loss prediction model for unpaved roads in Uganda.

Chapter Seven

VALIDATION OF THE GRCI MODEL THROUGH APPLICATION ON A CASE-STUDY GRAVEL ROAD

7.1 Introduction

This chapter discusses the GRCI model validation that was done through the application of the model on a case-study gravel road. The GRCI model was applied on the Misindye-Kiyunga Road *(shown in Figure 7.1)* using the GRCI condition assessment form developed by this researcher that records the severity value of each of the weighted nine (09) distresses for a maximum of 1km per section. The results from the field-based observation were verified through comparison with the pre-existing condition assessment method (i.e., VCI) as discussed in the subsequent sections. Additionally, this chapter discusses the material test results, traffic and rainfall information that was required to develop a relationship between the GRCI and Annual Gravel Loss (AGL).

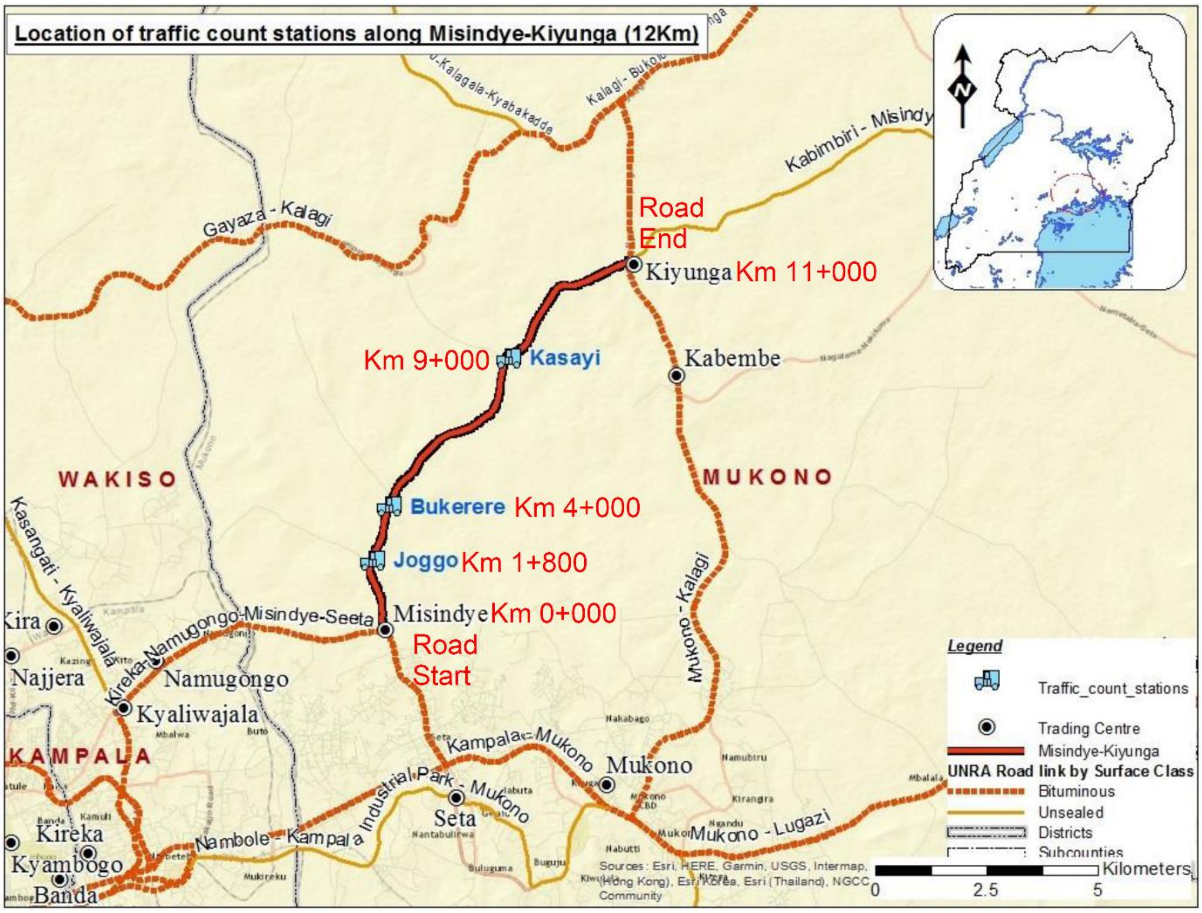


Figure 7.1: Location of the Misindye-Kiyunga Road on the Mukono District Map (UNRA, 2019)

7.2 The case-study gravel road

The Misindye-Kiyunga Road is an 11 kilometers long national gravel road located in Mukono District in the central region of Uganda *(see Figure 7.1)*. This gravel road starts at Misindye trading center off the Seeta-Namugongo Road and runs north-east to Kiyunga trading center located along the Mukono-Kalagi Road in Mukono District (UNRA, 2019). According to the Uganda Road Design Manual – Geometric Design Manual, under functional classifications, the road lies in class D Roads since it serves a dual function of accommodating shorter trips and feeding the higher classes. The road also links locally important traffic generators with their rural hinterland(UNRA, 2019).

The traffic information obtained from UNRA (2019) was essential in determining the Annual Gravel Loss (AGL) for the Misindye-Kiyunga Road as discussed in the succeeding section.

7.3 Annual Gravel Loss of the case-study road

Part of the objectives of this research study was to establish a relationship between the novel pavement condition assessment method (i.e., the GRCI) and the currently applied gravel loss prediction model for unpaved roads in Uganda. It was therefore important for this researcher to determine the Annual Gravel Loss (AGL) of the case-study road. This was achieved by establishing the variable values of the Ugandan AGL model since it predicts gravel loss as a function of traffic volume, rainfall, dust, and material properties.

7.3.1 Traffic volume

Traffic volume is a significant contributing factor to the AGL. According to UNRA (2019), traffic surveys on the case-study road were conducted using Manual Classified Counts (MCC). The Manual Classified Counts (MCCs) survey was composed of 3 stations located along the case-study road i.e., at Joggo, Bukerere and Kasayi as shown in Figure 7.1. The traffic volumes for 12 vehicle categories were recorded and each MCC survey was carried out for seven (7) days, with 5 days from 6 a.m. to 6 p.m., and 2 days (one on the weekend, one during working days) over 24 hours.

Table 7.1: Location of Traffic Count Stations (UNRA, 2019)

Station No.	StationName	Chainage
1	Joggo	1+800
2	Bukerere	4+000
3	Kasayi	9+000

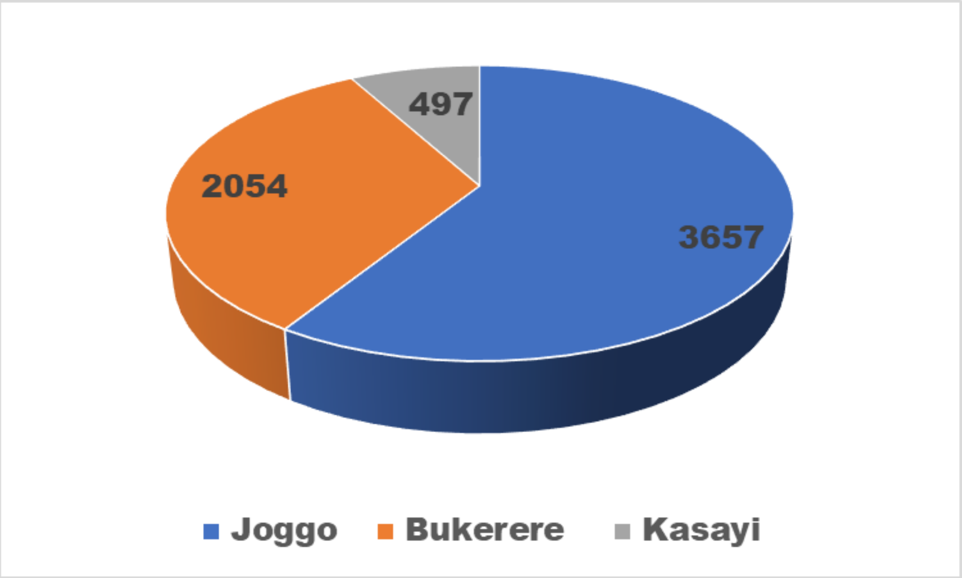


Figure 7.2: Total ADT at each Count Station (vehicles per day) (UNRA, 2019)

The Total Average Daily Traffic (ADT) in both directions (vehicles per day) at Joggo, Bukerere and Kasayi were recorded as 3,657, 2,054, and 497 respectively (UNRA, 2019). The section lengths of the case-study road applicable to the Joggo, Bukerere and Kasayi count stations were 3km, 5km, and 3km respectively.

Having obtained the ADT values at the three (03) count stations, this researcher proceeded to compute the weighted ADT since only one ADT value was required to compute the AGL of the case-study gravel road. The weighted ADT was computed using eq.7.1;

$$Weighted\ ADT = \frac{\sum Section\ Length\ x\ Section\ ADT}{\sum Section\ Length} \qquad (\boldsymbol{eq.7.1})$$

$$Weighted\ ADT = \frac{(3km\ x\ 3{,}657) + (5km\ x\ 2{,}054) + (3km\ x\ 497)}{(3km + 5km + 3km)}$$

$$\boldsymbol{Weighted\ ADT = 2{,}067}$$

7.3.2 Material properties

The Ugandan AGL model predicts gravel loss as a function of traffic volume, rainfall, dust, and material properties. The material properties are essential in determining the Dust Ratio (DR) and Grading Modulus (GM) which are key independent variables of the AGL model. This researcher, after acquiring approval from the Uganda National Roads Authority, carried out laboratory tests on soil samples obtained from excavated trial pits along the case-study road *(see example trial pit in Figure 7.3).*

Figure 7.3: Excavated Trial Pit (TP01) at Km 1+000

These trial pits were excavated at intervals of 1km along the case-study road totaling to 11 samples for the entire road length (i.e., 11 km). A particle size distribution test was conducted by an accredited laboratory to determine the soil index properties of each of the 11 samples. The results from the laboratory tests are summarized in Table 7.2 below and the detailed test results are attached as Appendix G of this thesis.

Table 7.2: Summary of laboratory test results of 11 samples

Trial Pit No.	Depth (mm)	P2.36	P0.425	P0.075	Dust Ratio (DR)	Grading Modulus (GM)
TP01	150	50	37	20	0.541	1.93
TP02	220	43	36	28	0.778	1.93
TP03	140	79	63	45	0.714	1.13
TP04	200	68	51	29	0.569	1.52
TP05	190	66	50	32	0.640	1.52
TP06	70	49	42	33	0.786	1.76
TP07	140	56	41	24	0.585	1.79
TP08	120	58	40	17	0.425	1.85
TP09	130	62	45	21	0.467	1.72
TP10	200	55	42	24	0.571	1.79
TP11	50	46	34	22	0.647	1.98

The Dust Ratio (DR) and Grading Modulus (GM) shown in Table 7.2 were calculated as follows;

DR = Dust ratio = P0.075 / P0.425

GM = [300-(P2.36 +P0.425 +P0.075)]/100

and where; P2.36 = percentage passing 2.36 mm sieve

P0.425 = percentage passing 0.425mm sieve

P0.075 = percentage passing 75µm sieve

7.3.3 Rainfall

Rainfall is another key independent variable of the Ugandan AGL model. This researcher obtained the Mean Monthly Rainfall data from the Uganda National Meteorological Authority for Mukono District *(see Table 7.3)*. Because the case-study road is located in the central region of Uganda, rainfall received is significant due to Mukono District having a tropical climate. The case-study road area receives an average of 260 mm in the month of May and 38mm in the month of December which is considered the driest month.

Table 7.3: Mean monthly rainfall (mm) for Mukono Station

Months	Totals (mm)
Jan	167.9
Feb	82.6

Months	Totals (mm)
Mar	166.3
Apr	164.4
May	260.7
Jun	123.8
Jul	67.2
Aug	77.1
Sep	94.1
Oct	192.6
Nov	143.8
Dec	38.6

7.3.4 Calculation of the AGL values for the road sections

Having obtained all the independent variable information, this researcher proceeded to calculate the AGL values for the eleven (11) different sections on the case-study road. The calculations were made in accordance with Equation 7.2 below that was developed by Were-Higenyi et. al. (2006) as discussed in subsection 3.3.1.6 of this thesis.

AGL = 8.4 + 0.258 (MMP)(ADT) + 55.02 (MMP) (DR)(GM) ***(eq.7.2)***

Where, AGL = Annual Gravel Loss (mm/year)

ADT = Average Daily Traffic, both directions (vehicles per day)

MMP = Mean Monthly Precipitation (m)

DR = Dust ratio = P0.075 / P0.425

GM = [300-(P2.36 +P0.425 +P0.075)]/100

and where; P2.36 = percentage passing 2.36 mm sieve

P0.425 = percentage passing 0.425mm sieve

P0.075 = percentage passing 75μm sieve

Applying Equation 7.2 to each of the eleven (11) sections of the case-study road generated the Annual Gravel Loss values in millimeters for each respective section as summarised in Table 7.4. This researcher, however, noted that the Average Daily Traffic (ADT) had a significant impact on the AGL values.

Table 7.4: Calculation of AGL values for each section of the case-study road

Road Section	MMP (m)	Weighted ADT	P2.36	P0.425	P0.075	Dust Ratio (DR)	Grading Modulus (GM)	Annual Gravel Loss (mm)
1	0.132	2067	50	37	20	0.541	1.93	86.4
2	0.132	2067	43	36	28	0.778	1.93	89.7
3	0.132	2067	79	63	45	0.714	1.13	84.7
4	0.132	2067	68	51	29	0.569	1.52	85.1
5	0.132	2067	66	50	32	0.640	1.52	85.9
6	0.132	2067	49	42	33	0.786	1.76	88.8
7	0.132	2067	56	41	24	0.585	1.79	86.4
8	0.132	2067	58	40	17	0.425	1.85	84.5
9	0.132	2067	62	45	21	0.467	1.72	84.6
10	0.132	2067	55	42	24	0.571	1.79	86.2
11	0.132	2067	46	34	22	0.647	1.98	88.1

7.4 Field based application of the GRCI

This researcher was granted permission by the Uganda National Roads Authority to carryout a pavement condition assessment on the Misindye-Kiyunga Road (11km) using the novel GRCI. This researcher applied the procedure discussed in subsection 6.7 of this thesis to carryout the condition assessment as follows;

- Step 1: Hold a pre-assessment meeting with the assessors and vehicle drivers.
- Step 2: Prepare the data collection sheets and tools prior to the assessment.
- Step 3: Carryout the condition assessment and provide a condition rating of each section of the assessed road length.
- Step 4: Determine the overall condition rating and condition category of the entire assessed road length.

This researcher will discuss each of the four (04) steps in the succeeding sections describing in detail how the steps were carried out in the field.

7.4.1 Step 1: Pre-assessment meeting

The first step of the field-based condition assessment was to hold a pre-assessment meeting on the case-study road with the assessors and vehicle drivers *(see Figure 7.4).*

Figure 7.4: Pre-assessment meeting on the Misindye-Kiyunga Road

During the meeting, a discussion was held between the two assessors to comprehend the GRCI condition assessment form that was used to record the severity values of each of the nine (09) identified distresses. The 5-point distress severity rating procedure *(described in subsection 6.4)* and the detailed distress severity classification *(shown in table 6.12)* were discussed so as to have a clear understanding of the 1 to 5 severity scale. Information was also provided to the vehicle drivers on how the assessment was to be carried out with emphasis placed on not exceeding a maximum vehicle traveling speed of 20km/hr.

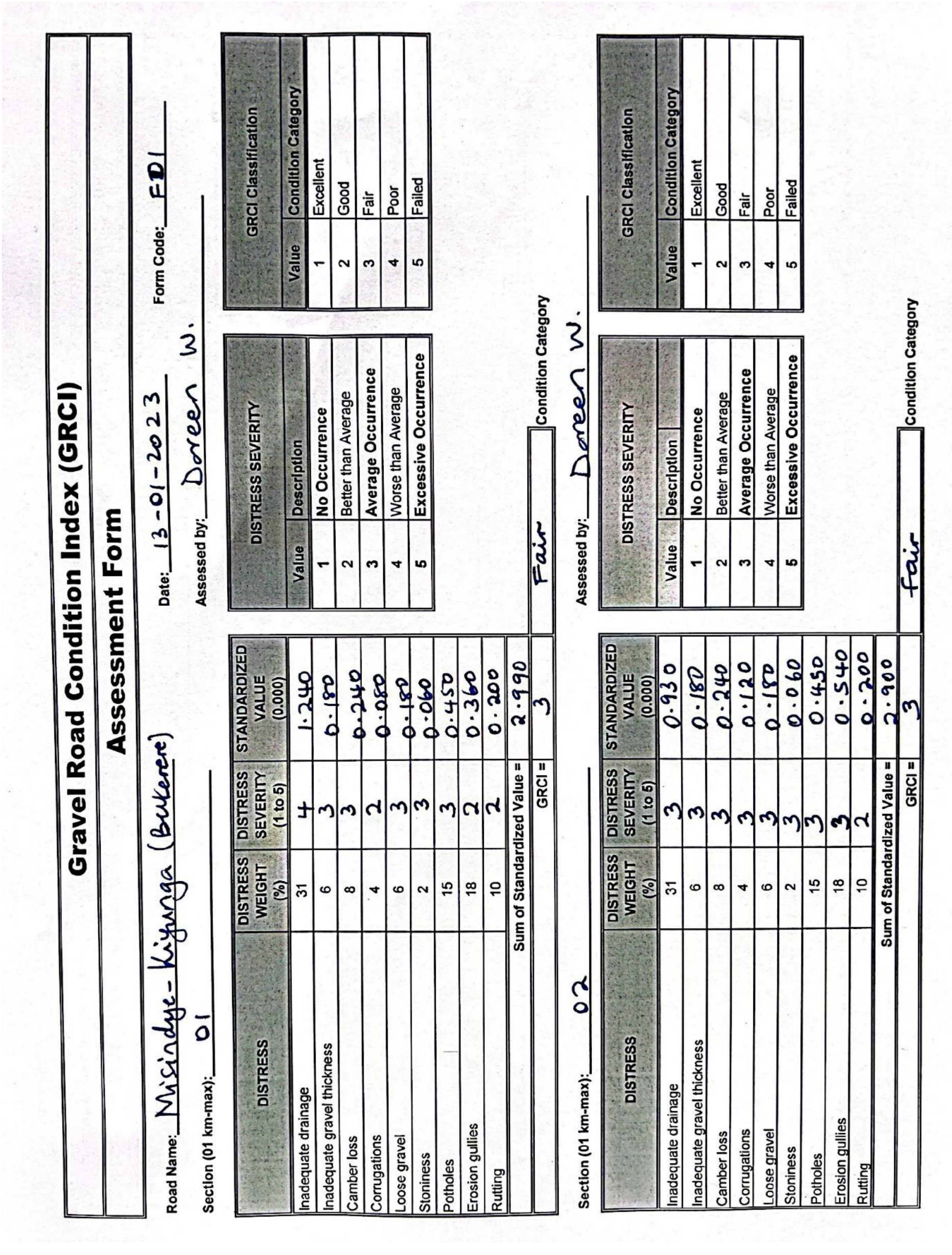
7.4.2 Step 2: Preparation of the data collection sheets and tools

The second step involved preparing the data collection sheets and tools. Each assessor was provided with ten (10) GRCI condition assessment forms. Ten forms were considered sufficient, being that each form records two (02) sections. The assessors were also provided clipboards, pens, and calculators to enable them record the severity values as well as calculate the standardised values.

7.4.3 Step 3: Carryout the condition assessment

Being a visual windshield survey, the third step involved carrying out the condition assessment with two assessors travelling in two separate vehicles. The assessors visually inspected a 1 km section, stopped and determined the GRCI rating of that section using the GRCI condition assessment forms, before proceeding to assess the subsequent section. This researcher deployed two assessors to ensure that a comparative analysis could be made for the results from the two assessors. This comparative analysis was made to ensure that the GRCI ratings had no repeatability concerns since it was a subjective manual condition assessment method.

Figure 7.5 below shows the populated GRCI assessment form of Assessor No.1 for section 1 and 2. The assessor recorded the road name, inspection date, assessors name, form code and the distress severity values between 1 and 5. These severity values were used to calculate the GRCI rating that defined the condition category of the assessed road section 1 and 2. Both Assessors No.1 and No.2 recorded the GRCI ratings and condition categories for all the 11 sections on the case-study road. The GRCI assessment forms for both assessors are attached as Appendix I of this thesis.



Gravel Road Condition Index (GRCI)

Assessment Form

Road Name: Misindye-Kiyunga (Bukerere)

Date: 13-01-2023 Form Code: FDI

Section (01 km-max): 01

Assessed by: Doreen W.

DISTRESS	DISTRESS WEIGHT (%)	DISTRESS SEVERITY (1 to 5)	STANDARDIZED VALUE (0.000)
Inadequate drainage	31	4	1.240
Inadequate gravel thickness	6	3	0.180
Camber loss	8	3	0.240
Corrugations	4	2	0.080
Loose gravel	6	3	0.180
Stoniness	2	3	0.060
Potholes	15	3	0.450
Erosion gullies	18	2	0.360
Rutting	10	2	0.200
		Sum of Standardized Value =	2.990
		GRCI =	3

Condition Category: Fair

Value	DISTRESS SEVERITY Description
1	No Occurrence
2	Better than Average
3	Average Occurrence
4	Worse than Average
5	Excessive Occurrence

Value	GRCI Classification Condition Category
1	Excellent
2	Good
3	Fair
4	Poor
5	Failed

Section (01 km-max): 02

Assessed by: Doreen W.

DISTRESS	DISTRESS WEIGHT (%)	DISTRESS SEVERITY (1 to 5)	STANDARDIZED VALUE (0.000)
Inadequate drainage	31	3	0.930
Inadequate gravel thickness	6	3	0.180
Camber loss	8	3	0.240
Corrugations	4	3	0.120
Loose gravel	6	3	0.180
Stoniness	2	3	0.060
Potholes	15	3	0.450
Erosion gullies	18	3	0.540
Rutting	10	2	0.200
		Sum of Standardized Value =	2.900
		GRCI =	3

Condition Category: fair

Value	DISTRESS SEVERITY Description
1	No Occurrence
2	Better than Average
3	Average Occurrence
4	Worse than Average
5	Excessive Occurrence

Value	GRCI Classification Condition Category
1	Excellent
2	Good
3	Fair
4	Poor
5	Failed

Figure 7.5: The populated GRCI condition assessment form of Assessor No.2 for section 1 and 2 of the Misindye-Kiyunga Road

7.4.4 Step 4: Determine the overall condition rating and condition category

The final step involved determining the overall condition rating and condition category of the Misindye-Kiyunga Road (11km). This was done by computing the weighted average of the GRCI ratings of the 11 sections of the case-study road. The results of the condition assessment for both assessors are summarised in Table 7.5.

Table 7.5: Calculation of the overall condition rating and condition category of the case-study road

Assessor No.1		
Gravel Road Condition Index (GRCI)		
Misindye-Kiyunga Road (11km)		
Road Section	**GRCI Rating**	**GRCI Condition Category**
1	3	Fair
2	4	Poor
3	3	Fair
4	3	Fair
5	3	Fair
6	3	Fair
7	3	Fair
8	2	Good
9	3	Fair
10	3	Fair
11	3	Fair
Overall Condition	**3**	**Fair**

Assessor No.2		
Gravel Road Condition Index (GRCI)		
Misindye-Kiyunga Road (11km)		
Road Section	**GRCI Rating**	**GRCI Condition Category**
1	3	Fair
2	3	Fair
3	3	Fair
4	3	Fair
5	3	Fair
6	3	Fair
7	3	Fair
8	3	Fair
9	3	Fair
10	3	Fair
11	3	Fair
Overall Condition	**3**	**Fair**

A comparison of the overall condition rating and condition category of Assessor No.1 and No.2 indicated that the case-study road was in a *"Fair"* condition. It was further noted that both assessors recorded the same overall rating indicating to this researcher that the GRCI had no repeatability concerns.

This researcher noted that for section 2, Assessor No.1 observed a *"Poor"* condition while Assessor No.2 observed a *"Fair"* condition. Similarly, for section 8, Assessor No.1 observed a *"Good"* condition while Assessor No.2 observed a *"Fair"* condition. It was however noted that having different ratings of section 2 and 8 did not affect the overall condition rating and condition category since it remained the same for both assessors.

7.5 Comparison between GRCI and VCI

The GRCI was validated through obtaining the condition ratings and condition categories of the 11 sections on the case-study road. This researcher also proceeded to verify the GRCI results through comparison with the existing Visual Condition Index (VCI) currently used by the Uganda National Roads Authority *(see subsection 2.8.2)*. Comparing the GRCI and VCI was done to establish whether a condition index with objective weights could have similar field results to an index having subjective weights. The condition information of the Misindye-Kiyunga Road with Road Code 678 and Road Name C045 was obtained from UNRA (2023) as summarized in Table 7.6.

Table 7.6: VCI rating and condition category of the Misindye-Kiyunga Road (UNRA, 2023)

Road Code	Road Name	Link	Segment	Weighted VCI	VCI Condition
678	C045	C04501	1	59.00	Fair
678	C045	C04501	2	60.25	Fair
678	C045	C04501	3	60.50	Fair
678	C045	C04501	4	64.25	Fair
678	C045	C04501	5	61.75	Fair
678	C045	C04501	6	64.25	Fair
678	C045	C04501	7	60.25	Fair
678	C045	C04501	8	64.25	Fair
678	C045	C04501	9	57.75	Fair
678	C045	C04501	10	64.25	Fair
678	C045	C04501	11	64.25	Fair
Overall Condition				**61.89**	**Fair**

VCI rating	VCI range
Very Good	86% to 100%
Good	71% to 85%
Fair	51% to 70%
Poor	31% to 50%
Very Poor	0% to 30%

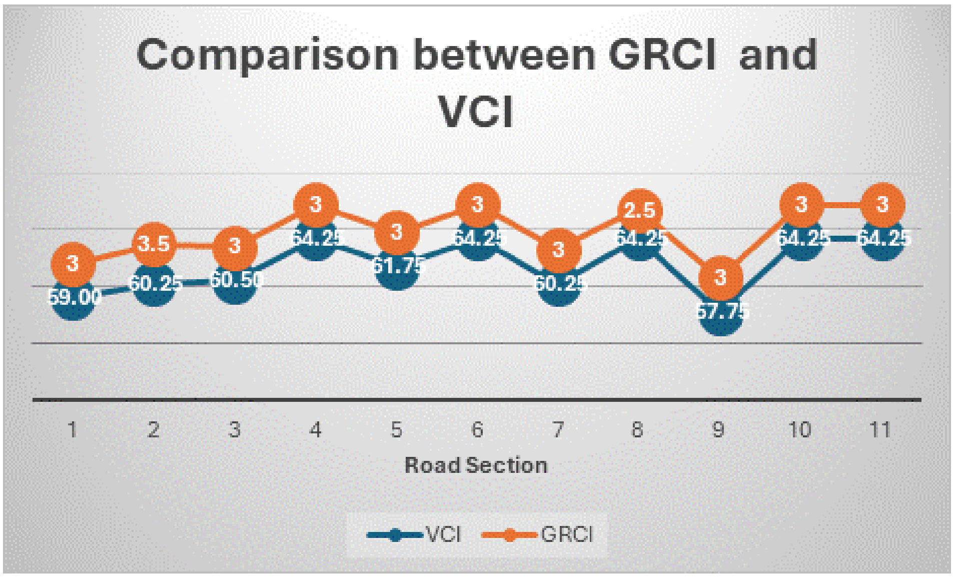


Figure 7.6: Comparison between GRCI and VCI

Because the VCI also has five (05) condition categories (i.e., Very Good, Good, Fair, Poor and Very Poor) it was therefore possible for this researcher to make a “like-for-like” comparison between the GRCI and the VCI. The overall condition category of the Misindye-Kiyunga Road was established as *“Fair”* with a VCI rating of 61.89. The comparison made by this researcher between the GRCI and VCI established that the results from both the condition assessment methods were similar i.e., both methods observed a *“Fair”* condition for the case-study road. Figure 7.6 indicates a section-by-section comparison between the GRCI and the VCI for each of the 11 sections of the case study road. The comparison indicated that the assessment results of the objective GRCI and the subjective VCI were similar and that the GRCI is consistent with the existing condition assessment method.

7.6 Establishing a relationship between GRCI and Annual Gravel Loss (AGL)

This researcher proceeded to establish a relationship between the Annual Gravel Loss *(derived in subsection 7.3.4)* and the GRCI obtained from the condition assessment. This was done by obtaining the Average Standardized Value (GRCI) from the two assessors and plotting against the AGL values determined for each of the 11 sections on the Misindye-Kiyunga Road.

Table 7.7: Average Standardized Value (GRCI) and AGL Value calculated for each section

Road Section	AVERAGE STANDARDIZED VALUE (GRCI)	AGL
1	3.105	86.4
2	3.220	89.7
3	2.755	84.7
4	2.745	85.1
5	2.985	85.9
6	3.065	88.8
7	2.950	86.4
8	2.445	84.5
9	3.010	84.6
10	2.790	86.2
11	3.100	88.1

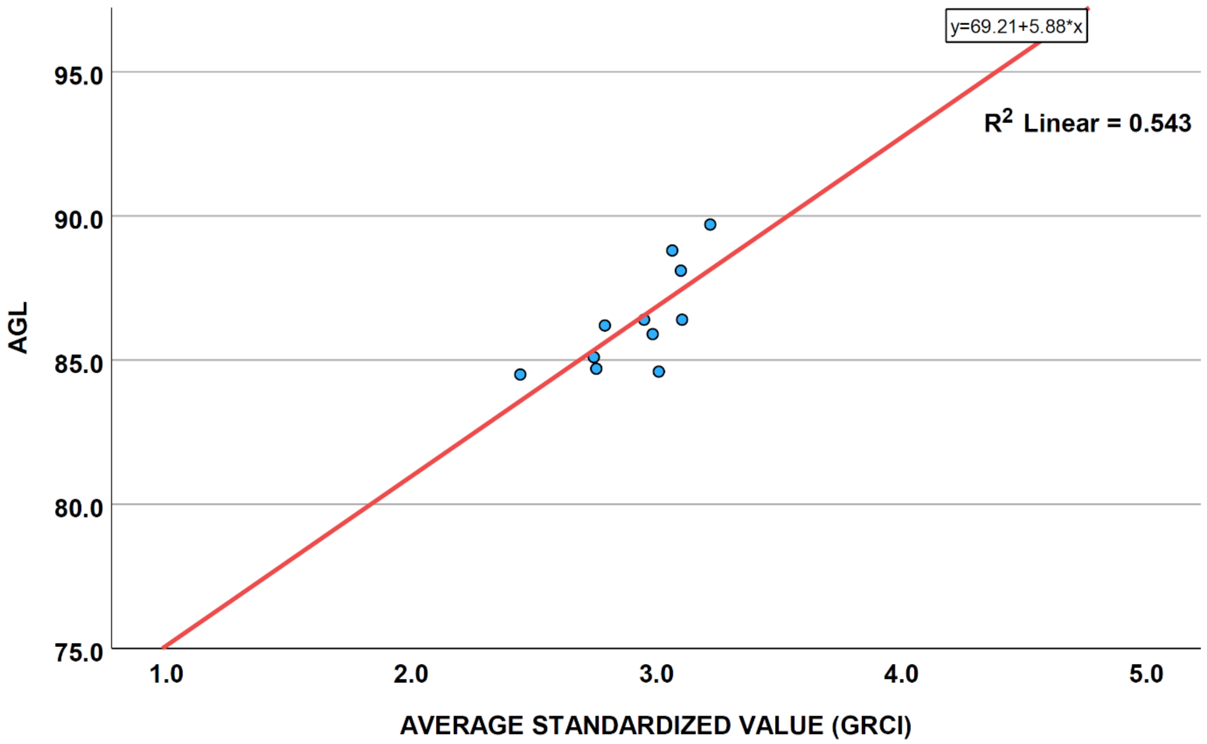


Figure 7.7: Scatter plot relationship between GRCI and AGL

The scatter plot in Figure 7.7 shows the *"line-of-fit"* indicating a correlation between the dependent variable, AGL, and the independent variable, GRCI. The linear regression model that describes the relationship between GRCI *(x)* and AGL *(y)* is shown in eq.7.3 below;

$$y = 69.21 + 5.88x \qquad (eq.\ 7.3)$$

Where; ***y*** = Annual Gravel Loss (AGL)

x = Gravel Road Condition Index (GRCI)

7.6.1 Application of the GRCI verses AGL relationship model

The relationship model developed in subsection 7.6 above can be used to predict future pavement deterioration. This is because the GRCI rating can predict the Annual Gravel Loss (AGL) of the case-study road. The application of the GRCI verses AGL relationship model was illustrated below, considering that the overall GRCI rating of the case-study road was 3.

$$y = 69.21 + 5.88x$$

Where, $x = 3$

$$y = 69.21 + 5.88(3)$$

$$y = 86.85$$

Therefore, the predicted Annual Gravel Loss (AGL) for the Misindye-Kiyunga Road was 86.85 millimeters.

7.6.2 Coefficient of Determination (R^2)

According to Mwaipungu (2015), the coefficient of determination (R^2) measures the proportion of variation in the dependent variable (AGL) that is explained by the independent variable (GRCI). R^2 has a value in the range of 0 to 1 and fundamentally measures how well the regression line predicts the data. The relationship model established by this researcher linking GRCI to AGL has an R^2 value of 0.543. This means that only 54.3% of the AGL value can be attributed to the GRCI rating.

The low coefficient of determination derived from the GRCI vs AGL relationship model indicates that the changing nature of unpaved roads under the influence of natural and human made variables, significantly affects the predictability of the distresses. Mwaipungu (2015) reaffirmed this observation stating that gravel loss models have significant variability and consequently relatively low R^2 values. It was noted that the regression model established by this researcher could be used to predict AGL from GRCI ratings despite the low R^2 value. This researcher, however, also noted that the relationship model of GRCI vs AGL had several limitations and that further studies needed to be carried out as discussed in subsection 8.4.

7.7 Summary of Chapter

In this chapter, the validation of the GRCI model through application on a case-study gravel road was discussed. This researcher validated and verified the GRCI by carrying out a condition assessment on the Misindye-Kiyunga Road. Two assessors were deployed to carryout the condition assessment which was done by visually inspecting a 1 km section, stopping, and determining the GRCI rating of that section using the GRCI condition assessment forms. Consequently, verification of the results was done by comparing the results from the GRCI with the existing Visual Condition Index (VCI) currently used by the Uganda National Roads Authority.

This researcher also determined the Annual Gravel Loss (AGL) of the case-study road to establish a relationship between the AGL and GRCI. This was done by establishing a linear regression model that described the relationship between the dependent variable, AGL, and the independent variable, GRCI. It was however noted that the resultant regression model could be used to predict AGL from GRCI ratings despite having a low coefficient of determination (R^2).

Chapter Eight

CONCLUSIONS AND RECOMMENDATIONS

8.1 Introduction

This final chapter of the thesis presents the conclusions and recommendations of the research study. Section 8.2 of this chapter restates and reviews the aims and objectives of this study and also describes how the objectives have been achieved. The succeeding section 8.3 illustrates the research study's contribution to both theory and practice. The limitations of the research study are discussed in section 8.4. Finally, section 8.5 discusses recommendations for further research study in pavement condition assessments for unpaved roads.

8.2 Synthesis of Research Findings

The aim of this research study, as discussed in section 1.3 of this thesis, was to develop a Gravel Road Condition Index (GRCI) assessment method for unpaved roads in Uganda. This GRCI model developed by applying the Analytic Hierarchy Process (AHP), can determine the condition rating of unpaved roads and also be used to predict future pavement deterioration. The overall research aim has been achieved by comprehensively investigating the four research objectives *(see section 1.3).* This has been achieved through carrying out an extensive and detailed literature review, questionnaire survey and case-study field investigations. The following sections outline a summary of the key research findings and how each objective has been fulfilled.

8.2.1 Achievement of Objective One

Objective One was *"To investigate current pavement condition assessment methods for unpaved roads and their related challenges".*

This objective was achieved by carrying out a comprehensive literature review. This researcher reviewed the existing pavement condition assessment methods for unpaved roads and discovered that they differ from country to country. It was however noted that the unpaved road network was usually managed by smaller local agencies with limited budgets. These budget limitations greatly affected the maintenance regimes of the local road agencies.

In the Ugandan context, it was discovered that local road agencies adopted a time dependent management policy instead of a condition dependent policy for managing pavements. This policy challenge coupled with lack of adequate funding for maintenance and rehabilitation activities meant that Uganda was unable to meet its road maintenance needs. It was established that the available funding met only 23.9% of the needs leaving 76.1% i.e., UGX 1.512 trillion ($410 million) of the maintenance needs unmet. This massive shortfall in maintenance funding implied that periodic maintenance activities were unfunded thereby leading to a deterioration in the condition of the road network. It was therefore necessary for Uganda to adopt a condition dependent policy for managing pavements so that maintenance funding is linked to the road condition.

Regarding condition assessment methods in Uganda, it was established that the National unpaved road network was assessed using the Visual Condition Index (VCI) which rates the road condition on a 5-point scale of Very Good (100) to Very Poor (0). On the other hand, the DUCAR agencies used the MoWT manual to measure the severity and extent of each distress using a 4-point grading for severity and a 5-point grading for the extent to determine the condition rating on a scale of 5 (Excellent) to 1 (Very Poor). This researcher, however, noted that both the VCI and MoWT methods were inadequate and could not be used to predict future pavement deterioration.

Based on the literature review, it was clear that despite the availability of condition assessment methods, Ugandan road agencies needed an improved condition assessment method for unpaved roads that would effectively and efficiently determine the condition rating of unpaved roads and also be used to predict future pavement deterioration.

8.2.2 Achievement of Objective Two

Objective Two was *"To review, identify and rank the high impacting road surface distresses that affect the condition rating of unpaved roads in Uganda".*

To achieve the aim of this research study, this researcher had to review, identify and rank the high impacting road surface distresses that affect the condition rating of unpaved roads in Uganda. An extensive and detailed literature review revealed that unpaved roads manifested nine (09) distresses i.e., Inadequate drainage, Inadequate gravel thickness, Camber loss, Corrugations, Loose gravel, Stoniness, Potholes, Erosion gullies and Rutting. A questionnaire survey was undertaken by this researcher to determine which of the nine (09) distresses identified from the literature review had the highest impact on the condition rating for unpaved roads in Uganda. The questionnaire was distributed to industry practitioners, such as road maintenance engineers, technicians and road inspectors who were located in at least one of the 23 districts that represented all the 06 regions in Uganda.

Results from the survey established that *"Inadequate drainage"* was ranked 1st with a mean value of 4.61 which meant that this road surface distress had the most severe impact on the condition rating. *"Erosion gullies"* were ranked 2nd with a mean value of 4.14 while *"Potholes"* came in 3rd with a mean value of 4.08. *"Rutting"*, *"Camber loss"* and *"Inadequate gravel thickness"* were ranked 4th, 5th, and 6th with mean values of 3.72, 3.67 and 3.56 respectively. *"Loose gravel"*, *"Corrugations"* and finally *"Stoniness"* were ranked 7th, 8th, and 9th with mean values of 3.56, 3.28 and 3.00 respectively.

Having achieved the second objective of identifying and ranking the high impacting road surface distresses that affect the condition rating of unpaved roads in Uganda, this researcher was then able to use the total scores to develop the Gravel Road Condition Index (GRCI).

8.2.3 Achievement of Objective Three

Objective Three was *"To develop a pavement condition assessment method, termed the Gravel Road Condition Index (GRCI), that will determine the condition rating of an unpaved road while also predicting future deterioration".*

This researcher established that an overall condition index could be obtained as a function of the weighting factor and severity combination for the nine (09) identified distresses. This researcher therefore proceeded to develop the Gravel Road Condition Index (GRCI) by deploying a mathematical model that took into account the weighting factors of each individual road surface distress.

These weighting factors were determined by making use of the Analytic Hierarchy Process (AHP) to convert the subjective survey results into objective mathematical data. The distress weighting factors were obtained, using the AHP method, by performing the following steps;

1. Define the goal and develop the AHP hierarchy.
2. Construct a pairwise comparison matrix.
3. Normalize the matrix by establishing the weighing.
4. Test for consistency.

Having obtained the distress weighting factors using the AHP method, this researcher developed a GRCI mathematical model based on the weighted sums method. The GRCI condition rating system, on the other hand, classified the condition of unpaved roads into five (05) categories i.e. *(1)* Excellent, *(2)* Good, *(3)* Fair, *(4)* Poor and *(5)* Failed. The GRCI was therefore represented by the mathematical model shown below.

$$\mathbf{GRCI = 0.31S_1 + 0.06S_2 + 0.08S_3 + 0.04S_4 + 0.06S_5 + 0.02S_6 + 0.15S_7 + 0.18S_8 + 0.1S_9}$$

Where; S_i = Distress Severity (Scale of 1 to 5)

The GRCI was also able to predict future deterioration because this researcher established a relationship between the GRCI and Annual Gravel Loss (AGL). This was done by plotting the GRCI rating against the AGL values determined for each of the 11 sections on the case-study road. A scatter plot was used to determine a correlation between the dependent variable, AGL, and the independent variable, GRCI. A linear regression model that described the relationship between GRCI *(x)* and AGL *(y)* was established as shown below. This researcher however noted that the relationship model of GRCI vs AGL had several limitations and that further studies needed to be carried out as discussed in subsection 8.4.

$$\mathbf{y = 69.21 + 5.88x}$$

Where; $\boldsymbol{y}$ = Annual Gravel Loss (AGL)

$\boldsymbol{x}$ = Gravel Road Condition Index (GRCI)

8.2.4 Achievement of Objective Four

Objective Four was *“To validate the GRCI and its application in Uganda.”*

The final objective involved validating the developed GRCI by applying the method on a case-study gravel road (i.e., by field observation). This researcher chose to apply the GRCI on the Misindye-Kiyunga Road (11km) because the road exhibited all the nine (09) identified distresses and because traffic information was readily available for this road. A condition assessment procedure for applying the GRCI was established as follows;

- Step 1: Hold a pre-assessment meeting with the assessors and vehicle drivers.
- Step 2: Prepare the data collection sheets and tools prior to the assessment.
- Step 3: Carryout the condition assessment and provide a condition rating of each section of the assessed road length.
- Step 4: Determine the overall condition rating and condition category of the entire assessed road length.

The above procedure enabled this researcher to determine the overall condition rating and condition category of the Misindye-Kiyunga Road (11km). Results from the case-study road application showed that the overall condition rating and condition category of Assessor No.1 and No.2 indicated that the case-study road was in a *“Fair”* condition. It was further noted that both assessors recorded the same overall rating indicating to this researcher that the GRCI had no repeatability concerns.

This researcher also verified the GRCI results through comparison with the existing Visual Condition Index (VCI) currently used by the Uganda National Roads Authority. The comparison made by this researcher between the GRCI and VCI established that the results from both the condition assessment methods were similar i.e., both methods observed a *“Fair”* condition for the case-study road. This researcher therefore verified that the results obtained from the GRCI on the case-study road were consistent with the existing condition assessment method.

8.3 Contribution to Knowledge and Practice

The significance of this research is demonstrated by its theoretical contributions to condition assessment methods for unpaved roads. This is the first research, according to this researcher's best knowledge, to enquire into the ranking of the high impact surface distresses that affect the condition rating of unpaved roads. This inquest was done using a questionnaire survey to industry practitioners, such as road maintenance engineers, technicians, and road inspectors. This research has identified nine (09) distresses following a comprehensive literature review that impact the condition of unpaved roads.

This is the first research to establish a relationship between pavement condition assessment ratings and gravel loss prediction models for unpaved roads. This research study has developed a linear regression model that indicates a correlation between the dependent variable, AGL, and the independent variable, GRCI. It is also essential to note that the improved pavement condition assessment method developed by this research study advances a more holistic understanding of the high impact surface distresses that affect the condition rating of unpaved roads. Additionally, this is the first research to develop an unpaved road condition assessment model whose weightings have been developed using the Analytic Hierarchy Process (AHP) that has converted subjective survey results into objective mathematical data.

In practice, this research study has established a method that will effectively and efficiently determine the condition of the unpaved road network in Uganda. This novel method addresses the limited assessment resources and colossal backlog in condition assessment because it is carried out using a rapid and inexpensive windshield survey. This new condition assessment method can be used by road maintenance engineers to quantify and cost maintenance and rehabilitation interventions basing on the condition rating of their respective unpaved road network. Additionally, this researcher has applied the new method on a case-study road and established that the GRCI had no repeatability concerns.

8.4 Limitations of the Research

Some limitations were noticed while conducting this research study. Because this research deployed a questionnaire survey for data collection, there were limitations regarding the number and response rates of participants. Though a reasonable response rate of 51.4% was achieved, it is the opinion of this researcher that the generalisation assumptions could have been improved with an even higher response rate. Furthermore, the target participant population consisted of practicing road maintenance engineers and managers in all the regions of Uganda. However, the high impact surface distresses that affect the condition rating of unpaved roads were selected by this researcher after carrying out a detailed literature review. It was thus observed in some of the responses from the participants that the selected number of distresses may have not been exhaustive.

Another limitation of the study was that the new method was considered subjective as it relied on the experience and understanding of the assessor. This concern was however addressed by the application of the new method on a case-study road with two assessors recording the same overall rating indicating that the GRCI had no repeatability concerns.

Because of limited time, resources and funding, this research study was unable to comprehensively validate the relationship between the GRCI and AGL. It was also noted that the correlation model developed by this researcher was based on only 11 points *(i.e., one (01) point for each kilometer).* Further research is therefore required on a longer gravel road network to comprehensively validate the relationship between the condition rating and the gravel loss predication model.

8.5 Recommendations for Further Research

Further research could be conducted to establish more credible approaches to developing condition assessment methods for unpaved roads. For example, weighting factors for the individual distresses could be calculated using other statistical methods such as factor analysis etc. as opposed to the Analytic Hierarchy Process (AHP) used in this study. Additionally, future research could widen the survey coverage to include other countries within Sub-Saharan Africa to create a generalised condition assessment model for road agencies with tropical climates.

Further research should be conducted to establish an appropriate Pavement Management System (PMS) with the GRCI values being the inputs for the condition information. This study scope did not include the development of a PMS that would be essential in assisting road maintenance engineers in Uganda have a workable one-stop center for planning and monitoring the performance of the unpaved road network in the Country. Integrating the GRCI into a broader asset management framework (PMS) could improve long-term planning and optimization of maintenance activities, considering the overall network condition, budget constraints, and road agency goals. Additionally, future research should be conducted to establish clear linkages between the GRCI and appropriate maintenance and rehabilitation activities for unpaved roads (e.g., grading, reshaping, spot gravelling, drainage improvement). This linkage could enable the development of decision-support tools that recommend optimal maintenance activities based on the assessed condition, taking into account factors such as cost-effectiveness, available resources, and the desired road service levels.

Lastly, this researcher contends that it is important to further understand the relationship between pavement condition assessment ratings and gravel loss prediction models for unpaved roads. It should be noted that the relationship model established by this researcher linking GRCI to AGL had an R^2 value of 0.543. This meant that only 54.3% of the AGL value could be attributed to the GRCI rating. This low coefficient of determination derived from the GRCI vs AGL relationship model indicated that the changing nature of unpaved roads under the influence of natural and human made variables, significantly affected the predictability of the distresses.

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Appendix A: Data Analysis Results from IBM SPSS Statistics

Statistics

		Inadequate drainage	Inadequate gravel thickness	Camber loss	Corrugations	Loose gravel
N	Valid	36	36	36	36	36
	Missing	0	0	0	0	0
Mean		4.61	3.56	3.67	3.28	3.56
Std. Deviation		.838	.909	.986	1.059	.998

Statistics

		Stoniness	Potholes	Erosion gullies	Rutting
N	Valid	36	36	36	36
	Missing	0	0	0	0
Mean		3.00	4.08	4.14	3.72
Std. Deviation		.926	1.079	1.018	.974

Frequency Tables

Inadequate drainage

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Insignificant impact	1	2.8	2.8	2.8
	Moderate impact	2	5.6	5.6	8.3
	Major impact	6	16.7	16.7	25.0
	Severe impact	27	75.0	75.0	100.0
	Total	36	100.0	100.0	

Inadequate gravel thickness

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Insignificant impact	1	2.8	2.8	2.8
	Minor impact	1	2.8	2.8	5.6
	Moderate impact	17	47.2	47.2	52.8
	Major impact	11	30.6	30.6	83.3
	Severe impact	6	16.7	16.7	100.0
	Total	36	100.0	100.0	

Camber loss

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Minor impact	5	13.9	13.9	13.9
	Moderate impact	10	27.8	27.8	41.7
	Major impact	13	36.1	36.1	77.8
	Severe impact	8	22.2	22.2	100.0
	Total	36	100.0	100.0	

Corrugations

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Insignificant impact	3	8.3	8.3	8.3
	Minor impact	3	8.3	8.3	16.7
	Moderate impact	15	41.7	41.7	58.3
	Major impact	11	30.6	30.6	88.9
	Severe impact	4	11.1	11.1	100.0
	Total	36	100.0	100.0	

Loose gravel

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Insignificant impact	1	2.8	2.8	2.8
	Minor impact	2	5.6	5.6	8.3
	Moderate impact	17	47.2	47.2	55.6
	Major impact	8	22.2	22.2	77.8
	Severe impact	8	22.2	22.2	100.0
	Total	36	100.0	100.0	

Stoniness

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Insignificant impact	2	5.6	5.6	5.6
	Minor impact	6	16.7	16.7	22.2
	Moderate impact	21	58.3	58.3	80.6
	Major impact	4	11.1	11.1	91.7
	Severe impact	3	8.3	8.3	100.0
	Total	36	100.0	100.0	

Potholes

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Insignificant impact	1	2.8	2.8	2.8
	Minor impact	2	5.6	5.6	8.3
	Moderate impact	7	19.4	19.4	27.8
	Major impact	9	25.0	25.0	52.8
	Severe impact	17	47.2	47.2	100.0
	Total	36	100.0	100.0	

Erosion gullies

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Insignificant impact	1	2.8	2.8	2.8
	Minor impact	2	5.6	5.6	8.3
	Moderate impact	4	11.1	11.1	19.4
	Major impact	13	36.1	36.1	55.6
	Severe impact	16	44.4	44.4	100.0
	Total	36	100.0	100.0	

Rutting

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Insignificant impact	1	2.8	2.8	2.8
	Minor impact	3	8.3	8.3	11.1
	Moderate impact	8	22.2	22.2	33.3
	Major impact	17	47.2	47.2	80.6
	Severe impact	7	19.4	19.4	100.0
	Total	36	100.0	100.0	

Appendix B: Reliability Analysis from IBM SPSS Statistics

Case Processing Summary

		N	%
Cases	Valid	36	100.0
	Excluded[a]	0	.0
	Total	36	100.0

a. Listwise deletion based on all variables in the procedure.

Reliability Statistics

Cronbach's Alpha	N of Items
.845	9

Item Statistics

	Mean	Std. Deviation	N
Inadequate drainage	4.61	.838	36
Inadequate gravel thickness	3.56	.909	36
Camber loss	3.67	.986	36
Corrugations	3.28	1.059	36
Loose gravel	3.56	.998	36
Stoniness	3.00	.926	36
Potholes	4.08	1.079	36
Erosion gullies	4.14	1.018	36
Rutting	3.72	.974	36

Item-Total Statistics

	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Cronbach's Alpha if Item Deleted
Inadequate drainage	29.00	29.371	.504	.835
Inadequate gravel thickness	30.06	29.540	.433	.841
Camber loss	29.94	28.454	.496	.835
Corrugations	30.33	26.229	.673	.816
Loose gravel	30.06	27.654	.571	.828
Stoniness	30.61	29.559	.420	.843
Potholes	29.53	26.371	.642	.820
Erosion gullies	29.47	27.228	.600	.824
Rutting	29.89	26.730	.691	.815

Scale Statistics

Mean	Variance	Std. Deviation	N of Items
33.61	34.644	5.886	9

Appendix C: Ethics Approval

Refresh View

Ethics Applications Home Screen Applicant

Your Applications

ID & Status	Title	Type	Decision
6440 Review Complete	DEVELOPING A PAVEMENT CONDITION ASSESSMENT METHOD FOR UNPAVED ROADS IN UGANDA.	Postgraduate Research	Approved

Appendix D: Survey Questionnaire

Ref. No [ ]

QUESTIONNAIRE BASED SURVEY

Research Title: ***DEVELOPING A PAVEMENT CONDITION ASSESSMENT METHOD FOR UNPAVED ROADS IN UGANDA***

This questionnaire is based on an ongoing PhD study which seeks to develop an improved pavement condition assessment method for unpaved roads in Uganda. The questionnaire intends to capture the road surface distresses that highly impact on the condition rating of unpaved roads in Uganda. As such this questionnaire is divided into two major parts as stated below;

Part A: Participant background information

Part B: High impact road surface distresses for unpaved roads

Survey Objective: To establish the high impact road surface distresses for unpaved roads in Uganda.

Confidentiality: The information collected will be used for the sole purpose of this study and for academic publications. The findings of the study will not be attributed to any specific participant.

Part A: Participant background information

Please tick √ the relevant box.

Qn.1: Which organization do you work for?

i. Uganda National Roads Authority (UNRA) ☐

ii. Uganda Road Fund (URF) ☐

iii. Ministry of Works and Transport (MoWT) ☐

iv. Local government agency ☐

v. Other organization (Please specify):…………………………………….

Qn.2: What is your highest academic qualification?

i. PhD ☐

ii. Masters degree ☐

iii. Post graduate degree ☐

iv. Undergraduate degree ☐

v. Tertiary qualification ☐

Qn.3: How long have you worked in the roads sector?

i. Less than 1 year ☐

ii. 1 to 2 years ☐

iii. 3 to 5 years ☐

iv. 5 to 10 years ☐

v. More than 10 years ☐

Qn.4: What is the total length (km) of unpaved roads under your management?

☐

Qn.5: Does your organization collect road condition data using a pavement condition assessment method for unpaved roads?

Yes ☐ No ☐

Qn.6: If yes, which unpaved road condition assessment do you use?

i. Visual Condition Index (VCI) ☐

ii. Ministry of Works and Transport (MoWT) Condition Rating ☐

iii. Annual District Inventory and Condition Survey (ADRICS) ☐

iv. Other condition assessment (Please specify):………………………………

Qn.7: Rate the ease of using the unpaved condition assessment method you have stated above? (Please rate from 1 to 5. Where, 1 = very easy and 5 = very hard)

1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐

Qn.8: How frequently does your organization carryout pavement condition assessments of your unpaved road network?

v. Monthly ☐

vi. Quaterly ☐

vii. Annually ☐

viii. Bi-Annually ☐

ix. Data collection is infrequent ☐

Qn.9: Can the condition rating derived from your pavement condition assessment be used to predict future pavement deterioration of unpaved roads?

Yes ☐ No ☐

Part B: High impact road surface distresses for unpaved roads

Qn.10: Of the road surface distresses listed below, which have the highest impact on the condition rating of unpaved roads in Uganda? Please use the 5-point Likert Scale as follows;

1 = Insignificant impact

2 = Minor impact

3 = Moderate impact

4 = Major impact

5 = Severe impact

Please tick √ the relevant box to indicate the highest impact on the condition rating of unpaved roads in Uganda.

S/N	Distresses	Impact				
		1	2	3	4	5
1	Inadequate drainage					
2	Inadequate gravel thickness					
3	Camber loss					
4	Corrugations					
5	Loose gravel					
6	Stoniness					
7	Potholes					
8	Erosion gullies					
9	Rutting					

Qn.11: Please list any other high impact road surface distresses for unpaved roads, which are not included in the above table. Please also indicate their degree of impact on the condition rating of unpaved roads in Uganda;

S/N	Distresses	Impact				
		1	2	3	4	5

Qn.12: Please add below any comments or views regarding this questionnaire;

Appendix E: Consent Form

RESEARCH PARTICIPANT CONSENT FORM

Research Title: *DEVELOPING A PAVEMENT CONDITION ASSESSMENT METHOD FOR UNPAVED ROADS IN UGANDA*

Name of researcher: *RICHARD MUSIIME*

Survey Objective: To establish the high impact road surface distresses for unpaved roads in Uganda.

Participant ID:

(Tick √ as appropriate)

STATEMENT	YES	NO
I understand that my participation in this survey is voluntary and that I am free to withdraw at any time without giving any reason.		
I understand that the information collected will be used for the sole purpose of this study and for academic publications only.		
I agree to take part in the above study.		

Name of participant: ………………………………………………………..

Signature:…………………………………………………………………..

Date:……………………………………………………………………….

Appendix F: Participant Invitation Letter

PARTICIPANT INVITATION LETTER

Dear Mr./ Mrs./ Ms.,

I am Richard Musiime a PhD candidate at The University of Salford (Manchester, UK) conducting a research study to develop an improved pavement condition assessment method for unpaved roads in Uganda.

Part of the research objectives of this study includes reviewing and identifying the high impacting road surface distresses that affect the condition rating of unpaved roads. This information will be used to develop a pavement condition assessment method, termed the Gravel Road Condition Index (GRCI). The GRCI will determine the condition rating of an unpaved road while also predicting future deterioration.

In order to make this research more beneficial and applicable, I would value your opinion about the road surface distresses that highly impact on the condition rating of unpaved roads in Uganda. I would greatly appreciate your help in achieving the aim of this research by completing and returning the questionnaire below.

This questionnaire is aimed at Engineers, Technicians and Road Inspectors working in road agencies such as the Uganda National Roads Authority (UNRA), Uganda Road Fund (URF), Ministry of Works and Transport (MoWT) and Local government agencies tasked with maintaining both national unpaved roads and DUCAR (District, Urban, Community and Access Roads).

Kindly respond to the questions in the attached questionnaire and return it to the undersigned or by email on or before **31st May 2022**. I sincerely assure you beyond reasonable doubt that the responses you will offer will be handled with utmost confidence and it is purely for academic purposes only. Your names and identity will not be used anywhere in the thesis for privacy. Please respond diligently as these responses will be analyzed and incorporated into the study.

Thank you in advance for your valued assistance.

Yours Faithfully,
Richard Musiime
PhD candidate
The University of Salford
Manchester, UK

Email addresses: richard.musiime@yahoo.com
r.musiime@edu.salford.ac.uk
WhatsApp Contact: +256 782 162566

Appendix G: Laboratory Test Results

F/TR/02 ISSUE 01

GETLAB LTD
YOUR RELIABLE ENGINEERING LABORATORY

TEST CERTIFICATE

P.O. BOX 100001,Kasangati.
Plot 1234 ,Namirembe Hillside Road,Kitettika,Wakiso.
Tel: +256 (0) 392 175 866
Email: info@getlab.co.ug
Web: www.getlab.co.ug

CLIENT: M/S Musiime Richard

PROJECT: Particle Size Distribution Test for Misindye-Kiyunga Roads

Issue Date: 19-Jan-2023

Serial No. : P2023029-001

Narrative Description:
Samples were delivered to the laboratory by the Client field representatives

Date Tested: 16-Jan-2023

Test Report: GETL/TR/MR/23/001
Location: Misindye-Kiyunga Roads

Date Received: 13-Jan-2023

Legend: LL Liquid Limit; PL Plastic Limit; PI Plasticity Index; PM Plasticity Modulus; OMC Optimum Moisture Content; MDD Maximum Dry Density

Lab Ref. No.	Test Location and Sequential Number	Trial Pit No:	Depth (m)	Soil Description	Soil Index Properties: Percent Passing Sieve (mm)																GM
					75.0	50.0	37.5	28.0	20.0	14.0	10.0	6.3	5.0	2.0	1.18	0.600	0.425	0.300	0.150	0.075	
G/S/23/001	9+00LHS	TP09	1.30	Sands	100	100	96	88	85	82	78	73	70	62	57	49	45	39	25	21	1.73
G/S/23/002	6+00RHS	TP06	0.70	Gravels	100	100	100	90	87	82	76	68	62	49	46	44	42	40	35	33	1.76
G/S/23/003	3+00 LHS	TP03	1.40	Silts/Clays	100	100	100	92	91	89	86	84	83	79	76	68	63	58	48	45	1.13
G/S/23/004	4+00RHS	TP04	2.00	Sands	100	100	100	100	96	91	86	80	77	68	63	56	51	46	34	29	1.52
G/S/23/005	1+00LHS	TP01	1.50	Gravels	100	100	92	89	83	79	72	63	59	50	46	40	37	32	23	20	1.93
G/S/23/006	10+00RHS	TP010	2.00	Gravels	100	100	97	92	87	80	75	67	64	55	53	47	42	37	27	24	1.79
G/S/23/007	11+050LHS	TP011	0.50	Gravels	100	100	100	99	89	83	77	67	61	46	41	36	34	31	24	22	1.98
G/S/23/008	5+00LHS	TP05	1.90	Gravels	100	100	100	96	94	88	84	79	75	66	61	54	50	46	36	32	1.52
G/S/23/009	8+00RHS	TP08	1.20	Gravels	100	100	100	93	88	82	77	70	67	58	54	46	40	35	21	17	1.85
G/S/23/010	7+00LHS	TP07	1.40	Gravels	100	100	100	97	90	85	78	70	66	56	52	45	41	37	27	24	1.80
G/S/23/011	2+000 RHS	TP02	2.20	Gravels	100	100	100	90	84	75	66	56	53	43	40	37	36	34	30	28	1.93

Note: Soil description is made according to AASHTO M145

Tested/Prepared by: Laboratory Engineer

Checked by: Senior Laboratory Engineer (M.J)

Approved by: Technical Manager (Dr.BS)

GETLAB LTD YOUR RELIABLE ENGINEERING LABORATORY 19 JAN 2023 Geotechnical Engineering & Technology Laboratory Ltd P. O. Box 100001, Kasangati

Notes:
1 DISCLAIMER-The results provided herein apply only to the samples that were tested
2 This test report shall not be reproduced except in full, without written approval of the laboratory
3 Interpretation of the results will be made at the request of the client/customer
4 The above test results applies to thesamples delivered by the client
5 NA-Not Applicable

---------END OF TEST CERTIFICATE---------

Appendix H: UNRA Permission Letter

Uganda National Roads Authority
Plot 3.5 New Port Bell Road, UAP Nakawa
Business Park Block C & D
P.O. Box 28487, Kampala Uganda
In any correspondence on this subject
Please quote No **UNRA/DNPE/SU/12/22**

22 December 2022

Richard Musiime,
PhD candidate,
The University of Salford,
Manchester, UK

REQUEST FOR PERMISSION TO CARRYOUT A PAVEMENT CONDITION ASSESSMENT ON THE MISINDYE-KIYUNGA (Bukerere) ROAD (11km)

Reference is made to your letter USM/UNRA/01 dated 20th December 2022 requesting for permission to carryout a pavement condition assessment on the Misindye-Kiyunga (Bukerere) Road (11km) as part of your PhD research study.

We have reviewed your request and have **no objection** with you carrying out this assessment to validate your new condition assessment method. We, however, request that the findings of the study are shared with our kind office for purposes of information sharing.

Eng. Isaac Wani
DIRECTOR NETWORK PLANNING AND ENGINEERING
IW/ha/npe

Copy to:

- *File*

Tel: +256 31 2233100 ▪ 256 414 318000 ▪ Fax: +256 414 232807, 347616 ▪ E-mail: executive@unra.go.ug ▪ Website: http://www.unra.go.ug

Appendix I: GRCI Assessment Forms for Assessor No.1 and No.2

Gravel Road Condition Index (GRCI)

Assessment Form

Road Name: Misindye- Kiyunga (Bukerere)   Date: 13-01-2023   Form Code: FDI

Section (01 km-max): 01   Assessed by: Doreen W.

DISTRESS	DISTRESS WEIGHT (%)	DISTRESS SEVERITY (1 to 5)	STANDARDIZED VALUE (0.000)
Inadequate drainage	31	4	1.240
Inadequate gravel thickness	6	3	0.180
Camber loss	8	3	0.240
Corrugations	4	2	0.080
Loose gravel	6	3	0.180
Stoniness	2	3	0.060
Potholes	15	3	0.450
Erosion gullies	18	2	0.360
Rutting	10	2	0.200
		Sum of Standardized Value =	2.990
		GRCI =	3

Fair — Condition Category

DISTRESS SEVERITY	
Value	Description
1	No Occurrence
2	Better than Average
3	Average Occurrence
4	Worse than Average
5	Excessive Occurrence

GRCI Classification	
Value	Condition Category
1	Excellent
2	Good
3	Fair
4	Poor
5	Failed

Section (01 km-max): 02   Assessed by: Doreen W.

DISTRESS	DISTRESS WEIGHT (%)	DISTRESS SEVERITY (1 to 5)	STANDARDIZED VALUE (0.000)
Inadequate drainage	31	3	0.930
Inadequate gravel thickness	6	3	0.180
Camber loss	8	3	0.240
Corrugations	4	3	0.120
Loose gravel	6	3	0.180
Stoniness	2	3	0.060
Potholes	15	3	0.450
Erosion gullies	18	3	0.540
Rutting	10	2	0.200
		Sum of Standardized Value =	2.900
		GRCI =	3

Fair — Condition Category

DISTRESS SEVERITY	
Value	Description
1	No Occurrence
2	Better than Average
3	Average Occurrence
4	Worse than Average
5	Excessive Occurrence

GRCI Classification	
Value	Condition Category
1	Excellent
2	Good
3	Fair
4	Poor
5	Failed

Gravel Road Condition Index (GRCI)

Assessment Form

Road Name: Misindye- Bukerere-Kiyunga

Date: 13-01-2023

Form Code: F02

Section (01 km-max): 03

Assessed by: Doreen

DISTRESS	DISTRESS WEIGHT (%)	DISTRESS SEVERITY (1 to 5)	STANDARDIZED VALUE (0.000)
Inadequate drainage	31	3	0.930
Inadequate gravel thickness	6	3	0.180
Camber loss	8	3	0.240
Corrugations	4	3	0.120
Loose gravel	6	3	0.180
Stoniness	2	3	0.060
Potholes	15	3	0.450
Erosion gullies	18	3	0.540
Rutting	10	3	0.300
		Sum of Standardized Value =	3.000
		GRCI =	3

Fair — Condition Category

DISTRESS SEVERITY	
Value	Description
1	No Occurrence
2	Better than Average
3	Average Occurrence
4	Worse than Average
5	Excessive Occurrence

GRCI Classification	
Value	Condition Category
1	Excellent
2	Good
3	Fair
4	Poor
5	Failed

Section (01 km-max): 04

Assessed by: Doreen

DISTRESS	DISTRESS WEIGHT (%)	DISTRESS SEVERITY (1 to 5)	STANDARDIZED VALUE (0.000)
Inadequate drainage	31	3	0.930
Inadequate gravel thickness	6	2	0.120
Camber loss	8	3	0.240
Corrugations	4	2	0.080
Loose gravel	6	3	0.180
Stoniness	2	3	0.060
Potholes	15	2	0.300
Erosion gullies	18	2	0.360
Rutting	10	2	0.200
		Sum of Standardized Value =	2.47
		GRCI =	3

Fair — Condition Category

DISTRESS SEVERITY	
Value	Description
1	No Occurrence
2	Better than Average
3	Average Occurrence
4	Worse than Average
5	Excessive Occurrence

GRCI Classification	
Value	Condition Category
1	Excellent
2	Good
3	Fair
4	Poor
5	Failed

Gravel Road Condition Index (GRCI)

Assessment Form

Road Name: Misindye- Kiyunga (Bukerere)

Date: 13-01-2023

Form Code: F03

Section (01 km-max): 05

Assessed by: Doreen W.

DISTRESS	DISTRESS WEIGHT (%)	DISTRESS SEVERITY (1 to 5)	STANDARDIZED VALUE (0.000)
Inadequate drainage	31	3	0.930
Inadequate gravel thickness	6	3	0.180
Camber loss	8	3	0.240
Corrugations	4	3	0.120
Loose gravel	6	3	0.180
Stoniness	2	3	0.060
Potholes	15	2	0.300
Erosion gullies	18	3	0.540
Rutting	10	3	0.300
		Sum of Standardized Value =	2.850
		GRCI =	3

Condition Category: Fair

DISTRESS SEVERITY	
Value	Description
1	**No Occurrence**
2	Better than Average
3	**Average Occurrence**
4	Worse than Average
5	**Excessive Occurrence**

GRCI Classification	
Value	Condition Category
1	Excellent
2	Good
3	Fair
4	Poor
5	Failed

Section (01 km-max): 06

Assessed by: Doreen W.

DISTRESS	DISTRESS WEIGHT (%)	DISTRESS SEVERITY (1 to 5)	STANDARDIZED VALUE (0.000)
Inadequate drainage	31	3	0.930
Inadequate gravel thickness	6	3	0.180
Camber loss	8	3	0.240
Corrugations	4	3	0.120
Loose gravel	6	3	0.180
Stoniness	2	3	0.060
Potholes	15	3	0.450
Erosion gullies	18	3	0.540
Rutting	10	3	0.300
		Sum of Standardized Value =	3.000
		GRCI =	3

Condition Category: Fair

DISTRESS SEVERITY	
Value	Description
1	**No Occurrence**
2	Better than Average
3	**Average Occurrence**
4	Worse than Average
5	**Excessive Occurrence**

GRCI Classification	
Value	Condition Category
1	Excellent
2	Good
3	Fair
4	Poor
5	Failed

Gravel Road Condition Index (GRCI)

Assessment Form

Road Name: ____________ Date: 13-01-2023 Form Code: F 04

Section (01 km-max): 07 Assessed by: Doreen W.

DISTRESS	DISTRESS WEIGHT (%)	DISTRESS SEVERITY (1 to 5)	STANDARDIZED VALUE (0.000)
Inadequate drainage	31	4	1.240
Inadequate gravel thickness	6	3	0.180
Camber loss	8	3	0.240
Corrugations	4	3	0.120
Loose gravel	6	3	0.180
Stoniness	2	3	0.060
Potholes	15	2	0.300
Erosion gullies	18	2	0.360
Rutting	10	2	0.200
		Sum of Standardized Value =	2.88
		GRCI =	3

Condition Category: fair

DISTRESS SEVERITY	
Value	Description
1	No Occurrence
2	Better than Average
3	Average Occurrence
4	Worse than Average
5	Excessive Occurrence

GRCI Classification	
Value	Condition Category
1	Excellent
2	Good
3	Fair
4	Poor
5	Failed

Section (01 km-max): 08 Assessed by: Doreen W.

DISTRESS	DISTRESS WEIGHT (%)	DISTRESS SEVERITY (1 to 5)	STANDARDIZED VALUE (0.000)
Inadequate drainage	31	3	0.930
Inadequate gravel thickness	6	3	0.180
Camber loss	8	3	0.240
Corrugations	4	3	0.120
Loose gravel	6	3	0.180
Stoniness	2	3	0.060
Potholes	15	2	0.300
Erosion gullies	18	2	0.360
Rutting	10	3	0.300
		Sum of Standardized Value =	2.67
		GRCI =	3

Condition Category: fair

DISTRESS SEVERITY	
Value	Description
1	No Occurrence
2	Better than Average
3	Average Occurrence
4	Worse than Average
5	Excessive Occurrence

GRCI Classification	
Value	Condition Category
1	Excellent
2	Good
3	Fair
4	Poor
5	Failed

Gravel Road Condition Index (GRCI)

Assessment Form

Road Name: Misindye- Kiyunga (Bukerere) Date: 13-01-2023 Form Code: F05

Section (01 km-max): 09 Assessed by: Doreen W.

DISTRESS	DISTRESS WEIGHT (%)	DISTRESS SEVERITY (1 to 5)	STANDARDIZED VALUE (0.000)
Inadequate drainage	31	3	0.930
Inadequate gravel thickness	6	3	0.180
Camber loss	8	3	0.240
Corrugations	4	3	0.120
Loose gravel	6	3	0.180
Stoniness	2	4	0.080
Potholes	15	3	0.450
Erosion gullies	18	3	0.540
Rutting	10	3	0.300
		Sum of Standardized Value =	3.02
		GRCI =	3

Fair Condition Category

DISTRESS SEVERITY	
Value	Description
1	No Occurrence
2	Better than Average
3	Average Occurrence
4	Worse than Average
5	Excessive Occurrence

GRCI Classification	
Value	Condition Category
1	Excellent
2	Good
3	Fair
4	Poor
5	Failed

Section (01 km-max): 10 Assessed by: Doreen W.

DISTRESS	DISTRESS WEIGHT (%)	DISTRESS SEVERITY (1 to 5)	STANDARDIZED VALUE (0.000)
Inadequate drainage	31	3	0.930
Inadequate gravel thickness	6	3	0.180
Camber loss	8	3	0.240
Corrugations	4	2	0.080
Loose gravel	6	3	0.180
Stoniness	2	2	0.040
Potholes	15	2	0.300
Erosion gullies	18	3	0.540
Rutting	10	4	0.400
		Sum of Standardized Value =	2.890
		GRCI =	3

Fair Condition Category

DISTRESS SEVERITY	
Value	Description
1	No Occurrence
2	Better than Average
3	Average Occurrence
4	Worse than Average
5	Excessive Occurrence

GRCI Classification	
Value	Condition Category
1	Excellent
2	Good
3	Fair
4	Poor
5	Failed

Gravel Road Condition Index (GRCI)

Assessment Form

Road Name: Misindye- Kiyunga (Buterere)   Date: 13-01-2023   Form Code: F 06

Section (01 km-max): 11   Assessed by: Doreen W.

DISTRESS	DISTRESS WEIGHT (%)	DISTRESS SEVERITY (1 to 5)	STANDARDIZED VALUE (0.000)
Inadequate drainage	31	4	1.240
Inadequate gravel thickness	6	3	0.180
Camber loss	8	3	0.240
Corrugations	4	3	0.120
Loose gravel	6	3	0.180
Stoniness	2	3	0.060
Potholes	15	2	0.300
Erosion gullies	18	3	0.540
Rutting	10	4	0.400
		Sum of Standardized Value =	3.260
		GRCI =	3

Condition Category: fair

DISTRESS SEVERITY	
Value	Description
1	No Occurrence
2	Better than Average
3	Average Occurrence
4	Worse than Average
5	Excessive Occurrence

GRCI Classification	
Value	Condition Category
1	Excellent
2	Good
3	Fair
4	Poor
5	Failed

Section (01 km-max):   Assessed by:

DISTRESS	DISTRESS WEIGHT (%)	DISTRESS SEVERITY (1 to 5)	STANDARDIZED VALUE (0.000)
Inadequate drainage	31		
Inadequate gravel thickness	6		
Camber loss	8		
Corrugations	4		
Loose gravel	6		
Stoniness	2		
Potholes	15		
Erosion gullies	18		
Rutting	10		
		Sum of Standardized Value =	
		GRCI =	

Condition Category

DISTRESS SEVERITY	
Value	Description
1	No Occurrence
2	Better than Average
3	Average Occurrence
4	Worse than Average
5	Excessive Occurrence

GRCI Classification	
Value	Condition Category
1	Excellent
2	Good
3	Fair
4	Poor
5	Failed

Gravel Road Condition Index (GRCI)

Assessment Form

Road Name: Misindye- Kiyunga (11Km)

Date: 13/01/2023

Form Code: F1

Section (01 km-max): 01

Assessed by: Richard Musiime

DISTRESS	DISTRESS WEIGHT (%)	DISTRESS SEVERITY (1 to 5)	STANDARDIZED VALUE (0.000)
Inadequate drainage	31	4	1.240
Inadequate gravel thickness	6	3	0.180
Camber loss	8	4	0.320
Corrugations	4	2	0.080
Loose gravel	6	3	0.180
Stoniness	2	3	0.060
Potholes	15	4	0.600
Erosion gullies	18	2	0.360
Rutting	10	2	0.200
		Sum of Standardized Value =	3.22
		GRCI =	3

Fair Condition Category

DISTRESS SEVERITY	
Value	Description
1	**No Occurrence**
2	Better than Average
3	**Average Occurrence**
4	Worse than Average
5	**Excessive Occurrence**

GRCI Classification	
Value	Condition Category
1	Excellent
2	Good
3	Fair
4	Poor
5	Failed

Section (01 km-max): 02

Assessed by: Richard

DISTRESS	DISTRESS WEIGHT (%)	DISTRESS SEVERITY (1 to 5)	STANDARDIZED VALUE (0.000)
Inadequate drainage	31	4	1.240
Inadequate gravel thickness	6	3	0.180
Camber loss	8	4	0.320
Corrugations	4	3	0.120
Loose gravel	6	3	0.180
Stoniness	2	3	0.060
Potholes	15	4	0.600
Erosion gullies	18	3	0.540
Rutting	10	3	0.300
		Sum of Standardized Value =	3.54
		GRCI =	4

Poor Condition Category

DISTRESS SEVERITY	
Value	Description
1	**No Occurrence**
2	Better than Average
3	**Average Occurrence**
4	Worse than Average
5	**Excessive Occurrence**

GRCI Classification	
Value	Condition Category
1	Excellent
2	Good
3	Fair
4	Poor
5	Failed

Gravel Road Condition Index (GRCI)

Assessment Form

Road Name: Misindye- Kiyunga (11Km)

Date: 13/01/2023

Form Code: F2

Section (01 km-max): 03

Assessed by: Richard. M

DISTRESS	DISTRESS WEIGHT (%)	DISTRESS SEVERITY (1 to 5)	STANDARDIZED VALUE (0.000)
Inadequate drainage	31	2	0.620
Inadequate gravel thickness	6	3	0.180
Camber loss	8	2	0.160
Corrugations	4	3	0.120
Loose gravel	6	3	0.180
Stoniness	2	3	0.060
Potholes	15	3	0.450
Erosion gullies	18	3	0.540
Rutting	10	2	0.200
		Sum of Standardized Value =	2.51
		GRCI =	3

Fair — Condition Category

DISTRESS SEVERITY	
Value	Description
1	**No Occurrence**
2	Better than Average
3	**Average Occurrence**
4	Worse than Average
5	**Excessive Occurrence**

GRCI Classification	
Value	Condition Category
1	Excellent
2	Good
3	Fair
4	Poor
5	Failed

Section (01 km-max): 04

Assessed by: Richard. M

DISTRESS	DISTRESS WEIGHT (%)	DISTRESS SEVERITY (1 to 5)	STANDARDIZED VALUE (0.000)
Inadequate drainage	31	3	0.930
Inadequate gravel thickness	6	3	0.180
Camber loss	8	3	0.240
Corrugations	4	3	0.120
Loose gravel	6	3	0.180
Stoniness	2	4	0.080
Potholes	15	3	0.450
Erosion gullies	18	3	0.540
Rutting	10	3	0.300
		Sum of Standardized Value =	3.02
		GRCI =	3

Fair — Condition Category

DISTRESS SEVERITY	
Value	Description
1	**No Occurrence**
2	Better than Average
3	**Average Occurrence**
4	Worse than Average
5	**Excessive Occurrence**

GRCI Classification	
Value	Condition Category
1	Excellent
2	Good
3	Fair
4	Poor
5	Failed

Gravel Road Condition Index (GRCI)

Assessment Form

Road Name: Misindye- Kiyunga (11Km) Date: 13/01/2023 Form Code: F3

Section (01 km-max): 05 Assessed by: Richard- M

DISTRESS	DISTRESS WEIGHT (%)	DISTRESS SEVERITY (1 to 5)	STANDARDIZED VALUE (0.000)
Inadequate drainage	31	3	0.930
Inadequate gravel thickness	6	3	0.180
Camber loss	8	3	0.240
Corrugations	4	3	0.120
Loose gravel	6	2	0.120
Stoniness	2	3	0.060
Potholes	15	3	0.450
Erosion gullies	18	4	0.720
Rutting	10	3	0.300
		Sum of Standardized Value =	3.12
		GRCI =	3

Fair Condition Category

DISTRESS SEVERITY	
Value	Description
1	**No Occurrence**
2	Better than Average
3	**Average Occurrence**
4	Worse than Average
5	**Excessive Occurrence**

GRCI Classification	
Value	Condition Category
1	Excellent
2	Good
3	Fair
4	Poor
5	Failed

Section (01 km-max): 06 Assessed by: Richard-M

DISTRESS	DISTRESS WEIGHT (%)	DISTRESS SEVERITY (1 to 5)	STANDARDIZED VALUE (0.000)
Inadequate drainage	31	4	1.240
Inadequate gravel thickness	6	3	0.180
Camber loss	8	3	0.240
Corrugations	4	3	0.120
Loose gravel	6	3	0.180
Stoniness	2	3	0.060
Potholes	15	3	0.450
Erosion gullies	18	2	0.360
Rutting	10	3	0.300
		Sum of Standardized Value =	3.130
		GRCI =	3

Fair Condition Category

DISTRESS SEVERITY	
Value	Description
1	**No Occurrence**
2	Better than Average
3	**Average Occurrence**
4	Worse than Average
5	**Excessive Occurrence**

GRCI Classification	
Value	Condition Category
1	Excellent
2	Good
3	Fair
4	Poor
5	Failed

Gravel Road Condition Index (GRCI)

Assessment Form

Road Name: Misindye- Kiyunga (11km) Date: 13/01/2023 Form Code: F4

Section (01 km-max): 07 Assessed by: Richard. M

DISTRESS	DISTRESS WEIGHT (%)	DISTRESS SEVERITY (1 to 5)	STANDARDIZED VALUE (0.000)
Inadequate drainage	31	3	0.930
Inadequate gravel thickness	6	3	0.180
Camber loss	8	3	0.240
Corrugations	4	3	0.120
Loose gravel	6	3	0.180
Stoniness	2	4	0.080
Potholes	15	3	0.450
Erosion gullies	18	3	0.540
Rutting	10	3	0.300
		Sum of Standardized Value =	3.020
		GRCI =	3

Fair Condition Category

DISTRESS SEVERITY	
Value	Description
1	**No Occurrence**
2	Better than Average
3	**Average Occurrence**
4	Worse than Average
5	**Excessive Occurrence**

GRCI Classification	
Value	Condition Category
1	Excellent
2	Good
3	Fair
4	Poor
5	Failed

Section (01 km-max): 08 Assessed by: Richard. M

DISTRESS	DISTRESS WEIGHT (%)	DISTRESS SEVERITY (1 to 5)	STANDARDIZED VALUE (0.000)
Inadequate drainage	31	2	0.620
Inadequate gravel thickness	6	2	0.120
Camber loss	8	2	0.160
Corrugations	4	3	0.120
Loose gravel	6	2	0.120
Stoniness	2	3	0.060
Potholes	15	2	0.300
Erosion gullies	18	3	0.540
Rutting	10	3	0.300
		Sum of Standardized Value =	2.220
		GRCI =	2

Good Condition Category

DISTRESS SEVERITY	
Value	Description
1	**No Occurrence**
2	Better than Average
3	**Average Occurrence**
4	Worse than Average
5	**Excessive Occurrence**

GRCI Classification	
Value	Condition Category
1	Excellent
2	Good
3	Fair
4	Poor
5	Failed

Gravel Road Condition Index (GRCI)

Assessment Form

Road Name: Misindye - Kiyunga (11km)

Date: 13/01/2023

Form Code: F5

Section (01 km-max): 09

Assessed by: Richard. M

DISTRESS	DISTRESS WEIGHT (%)	DISTRESS SEVERITY (1 to 5)	STANDARDIZED VALUE (0.000)
Inadequate drainage	31	3	0.930
Inadequate gravel thickness	6	3	0.180
Camber loss	8	3	0.240
Corrugations	4	3	0.120
Loose gravel	6	3	0.180
Stoniness	2	3	0.060
Potholes	15	3	0.450
Erosion gullies	18	3	0.540
Rutting	10	3	0.300
		Sum of Standardized Value =	3.000
		GRCI =	3

Fair — Condition Category

DISTRESS SEVERITY	
Value	Description
1	**No Occurrence**
2	Better than Average
3	**Average Occurrence**
4	Worse than Average
5	**Excessive Occurrence**

GRCI Classification	
Value	Condition Category
1	Excellent
2	Good
3	Fair
4	Poor
5	Failed

Section (01 km-max): 10

Assessed by: Richard. M

DISTRESS	DISTRESS WEIGHT (%)	DISTRESS SEVERITY (1 to 5)	STANDARDIZED VALUE (0.000)
Inadequate drainage	31	3	0.930
Inadequate gravel thickness	6	2	0.120
Camber loss	8	3	0.240
Corrugations	4	2	0.080
Loose gravel	6	2	0.120
Stoniness	2	3	0.060
Potholes	15	2	0.300
Erosion gullies	18	3	0.540
Rutting	10	3	0.300
		Sum of Standardized Value =	2.69
		GRCI =	3

Fair — Condition Category

DISTRESS SEVERITY	
Value	Description
1	**No Occurrence**
2	Better than Average
3	**Average Occurrence**
4	Worse than Average
5	**Excessive Occurrence**

GRCI Classification	
Value	Condition Category
1	Excellent
2	Good
3	Fair
4	Poor
5	Failed

Gravel Road Condition Index (GRCI)

Assessment Form

Road Name: Misindye- Kiyunga (11km) Date: 13/01/2023 Form Code: F6

Section (01 km-max): 11 Assessed by: Richard. M

DISTRESS	DISTRESS WEIGHT (%)	DISTRESS SEVERITY (1 to 5)	STANDARDIZED VALUE (0.000)
Inadequate drainage	31	3	0.930
Inadequate gravel thickness	6	2	0.120
Camber loss	8	3	0.240
Corrugations	4	3	0.120
Loose gravel	6	3	0.180
Stoniness	2	3	0.060
Potholes	15	3	0.450
Erosion gullies	18	3	0.540
Rutting	10	3	0.300
		Sum of Standardized Value =	2.940
		GRCI =	3

Fair Condition Category

DISTRESS SEVERITY	
Value	Description
1	**No Occurrence**
2	Better than Average
3	**Average Occurrence**
4	Worse than Average
5	**Excessive Occurrence**

GRCI Classification	
Value	Condition Category
1	Excellent
2	Good
3	Fair
4	Poor
5	Failed

Section (01 km-max): ____________ Assessed by: ____________

DISTRESS	DISTRESS WEIGHT (%)	DISTRESS SEVERITY (1 to 5)	STANDARDIZED VALUE (0.000)
Inadequate drainage	31		
Inadequate gravel thickness	6		
Camber loss	8		
Corrugations	4		
Loose gravel	6		
Stoniness	2		
Potholes	15		
Erosion gullies	18		
Rutting	10		
		Sum of Standardized Value =	
		GRCI =	

Condition Category

DISTRESS SEVERITY	
Value	Description
1	**No Occurrence**
2	Better than Average
3	**Average Occurrence**
4	Worse than Average
5	**Excessive Occurrence**

GRCI Classification	
Value	Condition Category
1	Excellent
2	Good
3	Fair
4	Poor
5	Failed