Development of a Framework for Addressing the Moisture Damage Potential in Flexible Road Pavements in New Zealand

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Abstract

An efficient road network system is essential for achieving the desired economic growth of any country and for maintaining the levels of service. Road network management is an expensive operation and the investment in this sector often constrained. The demand for road maintenance and therefore cost is increasing due to accelerated damage from traffic loading and moisture. Premature failing could often be attributed to moisture ingress, which in turns leads to accelerated failure. Through the sufficient provision of drainage these failures could be avoided.

Moisture damage is often referred to as a critical failure that can affect the levels of service and may cause expensive repair or replacement of road pavement. Therefore, the objectives of research are to develop a moisture damage risk assessment framework and verify its reliability and applicability in the drainage needs assessments of any road network. A Moisture Damage Risk Assessment (MDRA) framework has been formulated using moisture damage parameter data obtained from the road network in New Zealand. A preliminary framework was developed based on the literature review and field work in the network. The framework was further updated based on the application and comparative study of the risk analysis techniques that included Fuzzy Logic and Fault Tree Analysis. All of these assisted in developing the revised MDRA which has been implemented in the network (case studies) for evaluating the reliability and applicability of the framework.

Finally the framework has been tested for its ability to prioritise the road sections that are at risk of failure and the output has been compared with pavement conditions and other prioritisation frameworks such as the Forward Work Programme and the maintenance cost trends of the road network. Overall, the MDRA framework has been successful in predicting the appropriate moisture damage risk of any road sections and its application and importance in drainage needs assessments have been presented. The framework is ready to be implemented and further research can focus on the implementation of the MDRA in drainage needs assessments throughout New Zealand.

Dedication

To my beloved wife Mansura Tasnim Fayrooz who has to sacrifice a lot during the journey of the PhD.

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Glossary of Terms

AADT	Average Annual Daily Traffic
CAPTIF	Canterbury Accelerated Pavement Testing Indoor Facility
cm	Centimetre
DCP	Dynamic Cone Penetrometer
FWD	Falling Weight Deflectometer
FWP	Forward Work Programme
GPR	Ground Penetrating Radar
HWD	Heavy Weight Deflectometer
IRI	International Roughness Index
km	Kilometre
LTPP	Long Term Pavement Performance
LWD	Light Weight Deflectometer
m	Metre
mm	Millimetre
MD	Moisture Damage
MDRA	Moisture Damage Risk Assessment
MD_Risk	Moisture damage risk
NAASRA	It is used in Australia and New Zealand to report road roughness. One NAASRA count indicates the cumulative upward vertical movement of 15.2 mm of the rear axle of the car fitted with measuring device (Austroads, 2008a)
NOC	Network Outcomes Contract
NZ	New Zealand
NZTA	New Zealand Transport Agency
PERT	Project Evaluation and Review Technique
PSMC	Performance Specified Maintenance Contract
PSC	Performance Specified Contract
RAMM	Road Asset Maintenance and Management
SHRP	Strategic Highway Research Programme
SWCC	Soil Water Characteristic Curve
TDR	Time-Domain Reflectometer
Vpd	Vehicle per day

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Chapter 1: Introduction

1.1 Introduction

Roads and highways are prime components of any country's infrastructure. An effective and efficient road network system is essential for achieving desired economic growth and for maintaining level of service. New Zealand has given priority for providing a road network that is safe, reliable and efficient. The New Zealand government invested a total of \$4.5 billion from 2009 to 2012 for maintaining and improving the State Highway network (NZTA, 2013a). The objective of this strategic investment was to ensure an improved infrastructure that would support the creation of jobs and enhance the economic growth of the country. The road network plays a vital role through generating safe, effective journeys for people, providing robust routes for freight and linking communities together (NZTA, 2013b). Overall, the efficient management of the road network can be a positive attribute towards the economic growth of the country.

Maintaining a sound road infrastructure is not an easy task; rather it is expensive and requires proper planning, implementation and extensive monitoring of development activities. The key challenge is to maintain the balance between the demand for, and supply of, investment in infrastructure management. Due to increases in traffic volumes and loading, roads are deteriorating at a faster rate and creating huge demand on maintenance budgets in New Zealand. Coupled with this the Ministry of Transport adopted a policy, in 2011, for a flat investment over the next ten years for road maintenance (NZTA, 2014). One explanation for this strategy is to finish the projects under the 'Roads of National Significance' scheme by 2020. New Zealand road controlling authorities have to be proactive in managing the increasing demand in maintenance costs and the decreasing investment. One obvious response from the industry is to ensure efficient management of this investment. Another response might be to compromise maintenance standards in order to lower the costs (Henning and Costello, 2012a).

1.2 Moisture and Its Effect on Road Network Management

Moisture-induced damage is one of the major concerns for road controlling authorities. Here the term 'moisture in the road pavement' includes water either from precipitation or from the groundwater table. Variation in moisture content in the base and the sub-base courses over the years due to changes in season, water table height and precipitation has a significant impact on a pavement's strength and serviceability (Austroads, 2008a). The situation is exacerbated in the wet season due to an increase in sub-surface moisture levels and the inundation of road pavements for a prolonged time in the case of flooding. The extent of moisture-induced damage includes rutting, differential settlement related cracking, stripping, pumping, ravelling and finally, failure of the subgrade (Austroads, 2008a; Amiri, Nazarian & Fernando, 2009). Moisture is considered one of the deteriorating factors for major road pavements in Australasia. The majority of the road pavements in this region are low volume rural roads.

These low volume rural roads in New Zealand are composed of either bound or unbound stabilised granular base course with a thin chip seal layer (Werkmeister, Steven & Alabaster, 2006). The function of the base course is to distribute the traffic load evenly and reduce the stress on the subgrade. Whereas the chip seal layer is to prevent the ingression of water into the pavement, to improve the riding quality and also to increase the skid resistance of the road pavement. The pavement layers are designed to provide sufficient strength in order to limit the rutting and deformation under traffic loading (Dodds, Logan, Fulford, McLachlan & Patrick, 1999). However, research showed that moisture enter through the chip seal surface layer both in static and accelerated traffic conditions (Hussain, Wilson, Henning & Alabaster, 2011; Werkmeister et al., 2006). With an increase in axle loads, moisture can cause more damage to pavements such as accelerated rutting (permanent deformation of pavement layers), and alligator cracking (Huang, 2004). Consequently, there are growing concerns among researchers and practitioners about moisture damage in road pavements and the possible remedies through drainage improvement.

Road network management is an expensive operation and the expenses are increasing over time due to the expansion of road networks, and an increase in material and labour costs. Given that the rate of investment in network management is either flat or reducing over time, it is essential for road controlling authorities to minimise the risks of premature failure of road pavements. In addition to that the scope of risk management has been modified in New

Zealand due to the implementation of the Performance Specified Maintenance Contract (PSMC) model. In a performance specified contract, the risks associated with network management are transferred mostly to the network management organisations. The network managers have to be proactive in identifying the risks and taking proactive remedial actions for reducing their consequences. As moisture-related damage is a major component of pavement distress, there is scope for identifying the risks associated with unexpected failure in road pavements. The development of a risk profile for premature failure can reduce the risk of unexpected failure in road asset management. Pavement failures are the result of a critical factor or a combination of factors. Often it is difficult for the network manager to identify the critical damage factors that need to be minimised to reduce the risk of failure in road pavements. So a risk assessment based prediction framework can be developed and implemented to address the moisture damage or drainage-deficiency related issues in road network management. Overall, the research has scope to address different aspects of the development and implementation of the framework.

1.3 Problem Statement

A. Development of a Framework to Identify Moisture Damage Potential in Flexible Road Pavements

Drainage improvement programmes are mainly targeted to drain out excess surface and sub-surface waters out from the pavement and thus reduce the extent of moisture damage potential in or on road pavements. Major drainage programmes in road network management in New Zealand include the installation of kerb and channel, subsoil drains; reforming lined and unlined water channels and high shoulder lip removal. The prime functions of these drainage measures are to reduce the amount of water both from the surface and from the pavement structure because excess water into pavement formation can hamper the integrity of the road pavement. Therefore, practitioners in road network management often require identification of the road sections where these drainage programmes can be implemented. The questions often arising are;

- How to identify the road sections for drainage improvement?
- How to prioritise these road sections for drainage improvement within the limited resources?
- How to identify the optimum treatment or drainage improvement for any road section?

In order to address all of these issues a framework need to be established that can be utilised to identify and prioritise the road sections for drainage improvement. Currently there are some guidelines in place for these identification and prioritisation processes and some studies were conducted to address the issues. However, there is a requirement of framework that will utilise the field inspection, video survey, high speed Falling Weight Deflectometer (FWD) and laboratory test data and expert judgement. Such a framework should assist in identifying the road sections with moisture damage potential and prioritising the road sections for implementing the drainage improvement programmes.

B. Identification of the Appropriate Risk Analysis Model for the Framework

The appropriate risk analysis technique will be the key for the desired framework that can address the moisture damage issues in road pavements. The risk analysis techniques applicable for the framework are determined based on the characteristics of the input data and the desired platform of the risk analysis output. The questions generally asked are;

- What are the major risk analysis techniques used in previous researches and available in the literature?
- How many of these risk analysis techniques are applicable in the framework based on the nature of the data and required output?
- How the most effective risk analysis technique for the framework can be identified?

The literature review is expected to answer the majority of the questions, especially to identify the relevant risk analysis techniques. Then these risk analysis techniques can be used in the framework to verify its performance, especially in its ability to identify and prioritise road sections for drainage improvement programmes.

C. Evaluation of the Framework based on its Performances and Application

Finally the evaluation and the validation of the proposed framework has been a major area that needed to be addressed during the research. The framework has to be scrutinised based on its ability in predicting and identifying the road sections with moisture damage failure. The expected questions to be answered in the research are;

- Is the framework successful in predicting potential road sections for drainage improvement?
- Is the predicted risk corroborates with the actual pavement condition and performance of the road section?
- Is the predicted future maintenance similar with the actual strategy developed by the deterioration modelling of the road network?

1.4 Objectives of the Research

The research is aimed to develop a framework that can be implemented to identify the road sections that are at risk of premature failure due to moisture. In addition, these vulnerable road sections can be linked to the drainage needs of the network. The overall aim of the research is to develop a hands-on tool to utilise in prioritising the road sections that can be programmed for drainage improvement.

Therefore, the major objectives of the research are;

- To develop a framework for prioritising the road sections that are at risk of premature failure due to moisture;
- To compare and evaluate the performance of risk analysis techniques in order to select the optimum technique for the framework; and
- To verify the reliability and applicability of the framework in drainage needs assessments of the road network.

The framework can be utilised for evaluation of networks for premature failure in road pavements. It can be essential for assessing the Forward Works Programme (FWP) and future maintenance investment in any road network. The reliability and applicability of this framework are crucial therefore; a holistic approach for validation of the framework has been implemented using the data from a road network in New Zealand.

1.5 Scope and Structure of the Thesis

This research project is funded by a commercial entity that has been managing a road network under a performance-based contract in New Zealand. The road network is in the north-west region of the country. The research project was launched with a view to develop a framework to identify the drainage need of the network based on the available field inspection and test data. The research has to focus on the operation and maintenance data available from the road network. Due to the commercial nature of the research project the case studies were implemented mainly on the road network maintenance data. In addition, the data available for use in the research is mostly dependent on the maintenance philosophy of the organisation. However, the geology, road pavements, climate, precipitation, traffic volume, and pavement and subgrade composition of the network closely matched with major road networks in other parts of New Zealand. Thus, the framework can be replicated to use for any road network in New Zealand. The flowchart in Figure 1-1 shows the structure of the thesis.

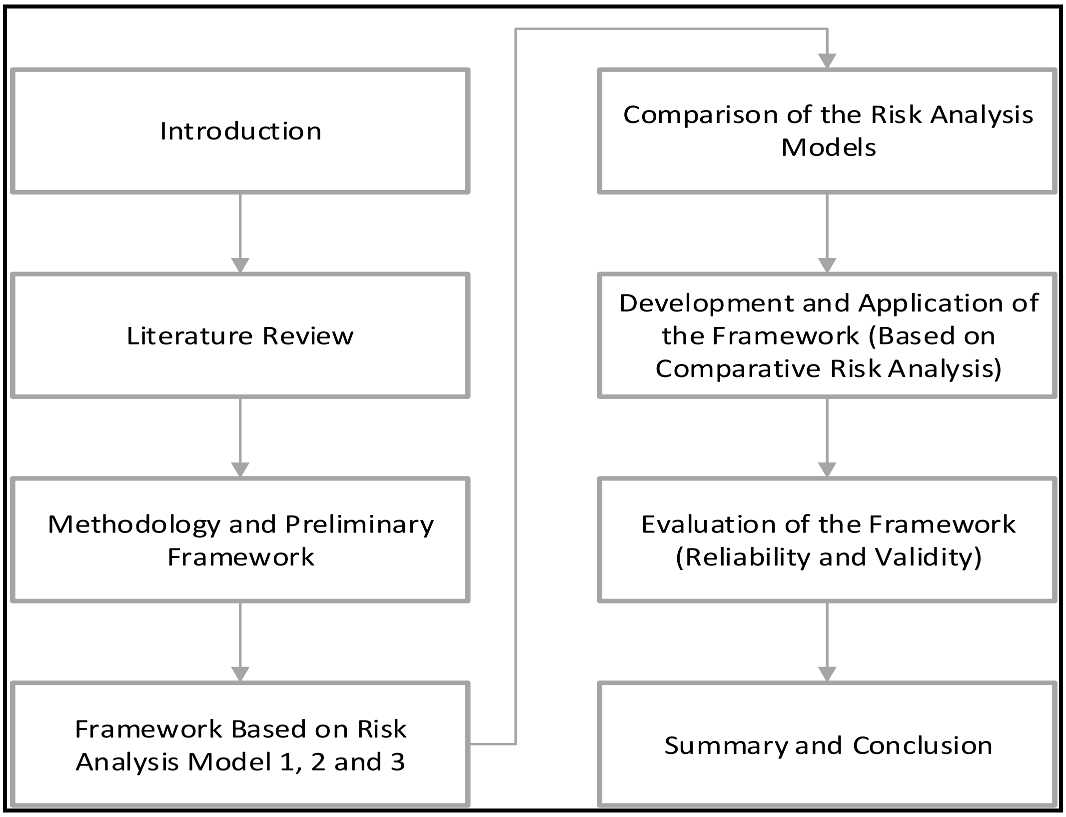


Figure 1-1 Major Contents of the Thesis

The introduction and the literature review give the background of the thesis. Topics included;

- Moisture damage in road pavements, various destructive and non-destructive test methods addressing moisture damages and different approaches to address moisture damage potential;
- Discussion on research conducted in different countries and especially in New Zealand, conducted to develop framework, methods and tests to address moisture damage potential in road pavements; and
- One major outcome of the literature review is to identify the candidate risk analysis models or techniques for the framework. The most risk analysis techniques found in the literature will be reviewed and the candidates will be selected based on their applicability in the research.

The research methodology will be presented in chapter 3 of the thesis. This involves the identification of the moisture damage factors and the conceptual development of the framework. The next three chapters are based on the development and application of the risk analysis models as part of the framework. The risk analysis techniques have to be developed based on the data or factors readily available for application in the framework and drainage needs assessments.

The next chapter deals with the comparative study of the three candidate risk analysis techniques used in the study. The indicators for performance evaluation of the risk analysis techniques include;

- Performance, speed, reliability, reproducibility and capacity of the risk analysis techniques;
- Applicability and reliability of the risk analysis techniques in road asset management; and
- Level of assumptions, limitations and availability of the risk analysis techniques.

This comparative study helps in modifying and developing the framework that has been evaluated and validated in the last part of the thesis. Topics include;

- Comparison of the predicted risk with actual performances and life cycle maintenance cost of the road pavement. Pavement distress issues such as rutting, roughness and skid resistance are considered during the evaluation of the framework; and
- Evaluating the prediction capability of the framework with future maintenance needs determined based on deterioration modelling.

Finally, the discussion chapter summarises the major outcomes, application of the research findings in drainage needs assessment. The conclusion chapter provides outcomes of the research in respect of the objectives and limitations of the research along with the recommendations for further research in the area of research.

Chapter 2: Literature Review

2.1 Introduction

The chapter provides the review of existing literature related to the effect of moisture in flexible road pavements. It begins with the review of studies on the following topics:

- Sources of moisture in road pavements;
- Mechanism of moisture damage in flexible road pavements;
- Different approaches of research in evaluating the performance of road pavements; and
- Application of deflection test for evaluating the performance and effect of moisture in road pavements

Later on, studies of New Zealand are summarised and based on this, a risk assessment framework has been conceptualised for evaluating the moisture damage potential on road pavements. Therefore, the review focuses on the various risk analysis techniques available in the literature. Overall, the literature review helps in developing a conceptual framework in order to meet the major objectives of the research.

2.2 Moisture in Road Pavements

The presence of excess moisture is attributed as one of the potential reasons for premature failure of road pavements. The amount of excess moisture for a particular road pavement depends on the designed Optimum Moisture Content (OMC). The design guideline of the modified AASHTO (American Association of State Highway and Transport Official) suggested 85% OMC for well drained and low water road section. Whereas, the design OMC should be 120% (soaked) as suggested by the modified AASHTO guideline for the road section at high water table, lack of adequate measure and may suffer occasional inundation due to flooding (Emery, Cocks, & Keeley, 2007).

The equilibrium moisture content in the road pavement is another concept that can be followed during quantification of the excess moisture. The degree of saturation which indicates the volumetric ratio of moisture and the pavement material can be used to define the amount of moisture in the road pavement. When the degree of saturation in road pavement reaches above the equilibrium moisture level, it could be considered as excess moisture. In New Zealand, the range of equilibrium moisture content was suggested to be from 50 to 60%. The equilibrium moisture level was suggested close to 85% for the subgrade material (Arampamoorthy & Patrick, 2010).

Engineers and pavement practitioners need to carefully consider the options for minimising the potential moisture-related distress in road pavements (Transit New Zealand, 2000). The term 'moisture in road pavements' includes water either precipitated as rain, snow, hail, sleet, or from the upward movement of the ground water table (O'Flaherty, 2002; Mallick & El-Korchi, 2009). In order to investigate moisture damage in road pavements, their sources need be understood. Figure 2-1 indicates the major sources of moisture in road pavements.

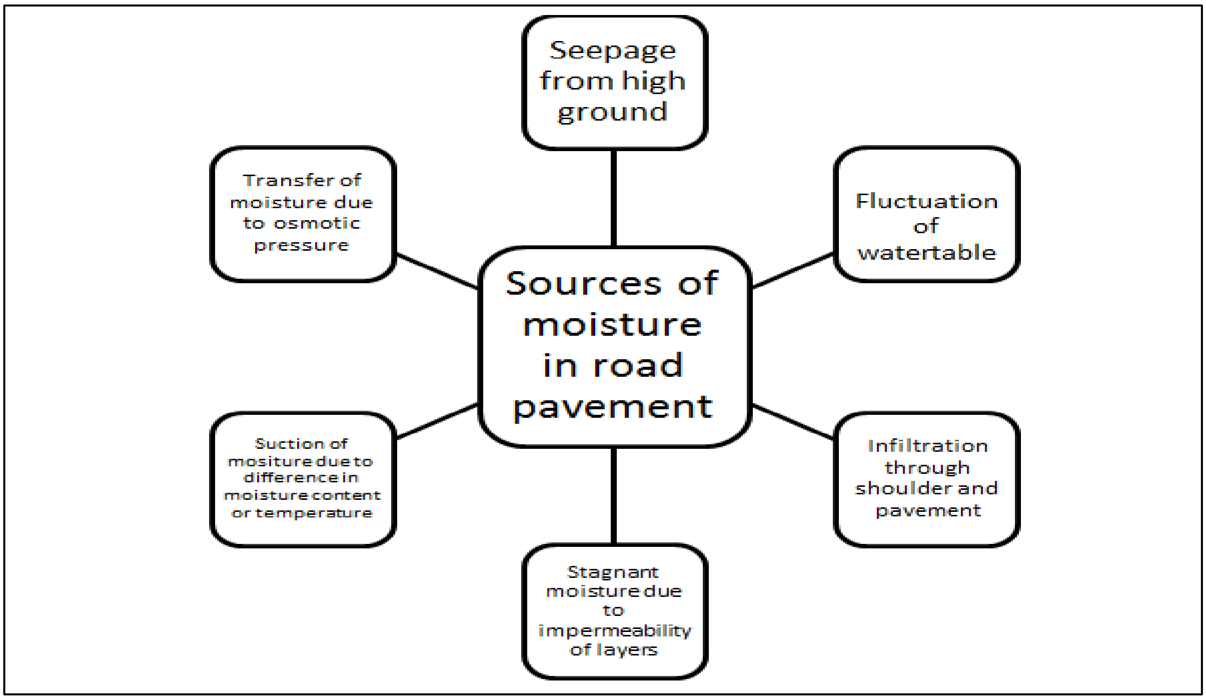


Figure 2-1 Source of Moisture in Road Pavements (Austroads, 2008a)

Among these, seepage from high ground and infiltrated moisture through the shoulder and pavement are of a similar nature and can be controlled by proper sub-surface drainage (Mallick & El-Korchi, 2009). If the sub-surface drainage or materials are not designed properly, there may be stagnant moisture in pavement layers. The capillary movement of water resulting from the fluctuation in the water table, or due to a difference in osmotic pressure, soil suction head may result in upward movement of water through cracks which is difficult to be controlled by sub-surface drainage (Austroads, 2008a). The sources of moisture and its relative flow in road pavements are shown in Figure 2-2.

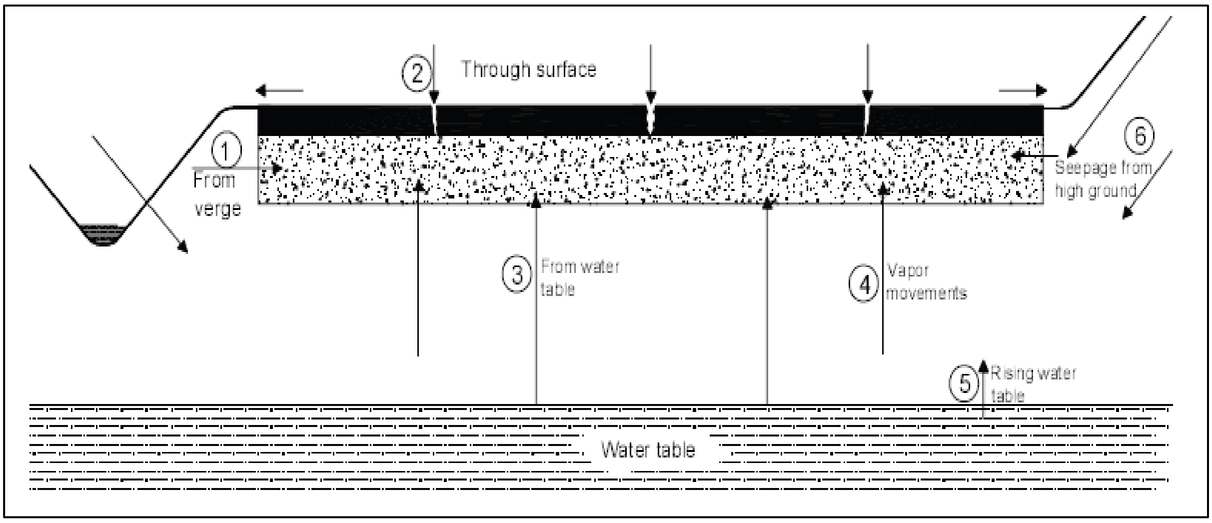


Figure 2-2 Source and Flow of Moisture in Road Pavements (Ekblad & Isacsson, 2006)

Water in the pavement from surface cracks (2), unsealed shoulders (1) and seepage from side hills (6) as shown in Figure 2-2 often become critical and need to be monitored. This water often saturates the granular base course and induces permanent deformation and premature failure in road pavements. The situation is worse in the case of road pavements under freeze-thaw conditions where the melted ice during thawing releases a substantial amount of water, causing saturation of the base layer (Ekblad & Isacsson, 2006). The vapour movement of water into the pavement (4) does not have a significant impact. However, water from the ground water table (3, 5) especially in areas of high water table and close to water sources, need to be considered during the design of pavement level and drainage (Ekblad & Isacsson, 2006). In order to examine the effect of moisture on road pavements, the factors presented in Figure 2-3 need to be considered.

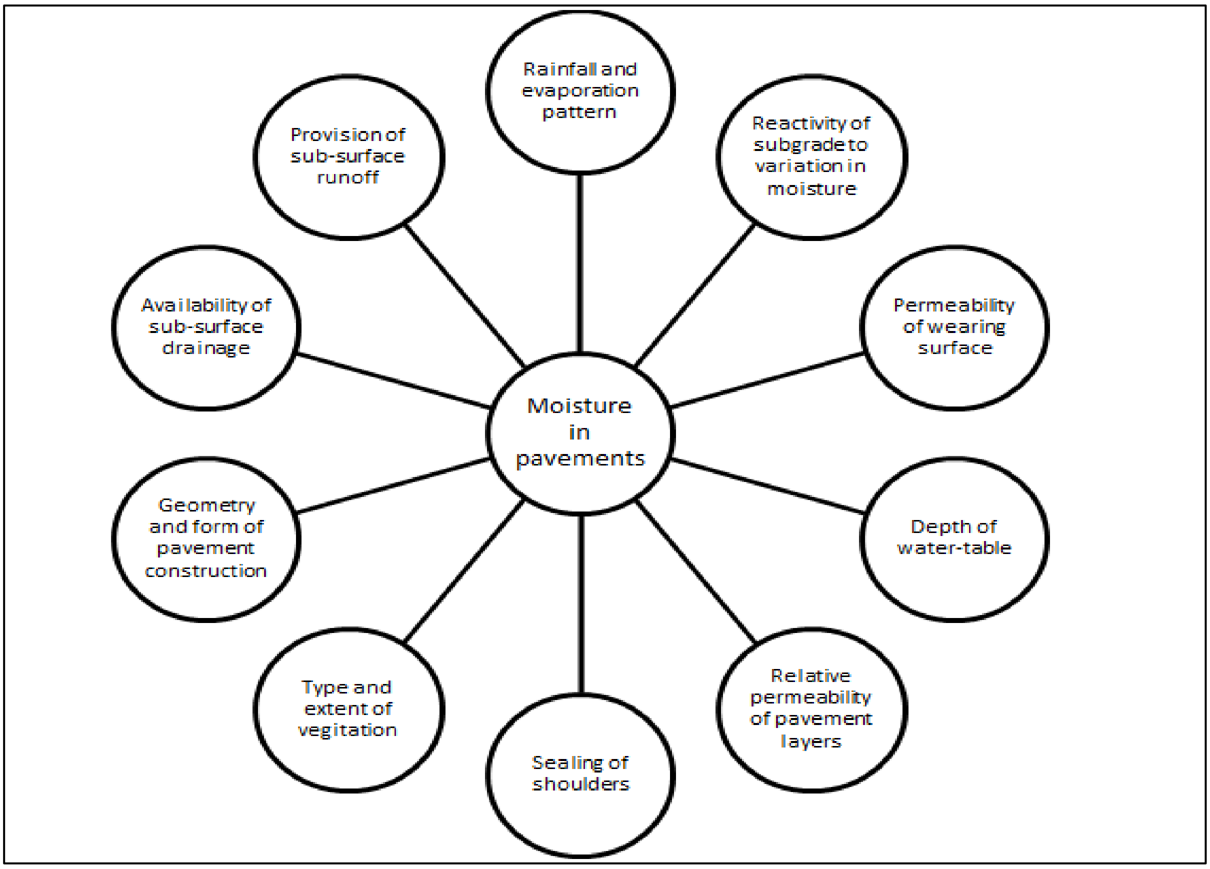


Figure 2-3 Factors Influencing the Moisture in Road Pavements (Austroads, 2008a)

Austroads suggested that the extent of rainfall (Figure 2-3) might be related to the pavement moisture condition, however, recent research suggested that no positive correlation was found between rainfall and pavement moisture condition (Peploe, 2002). Moisture sensitivity of subgrade materials is particularly important and generally finer grained materials compared to the coarser grained have changes in volume (increase) and strength (reduction) due to a rise in moisture content.

The effect of excess moisture on soil properties can be expressed by the Soil Water Characteristic Curve (SWCC). Figure 2-4 shows the SWCC prediction model developed for both the plastic and non-plastic materials. It provides the relationship between the moisture content of the unsaturated soil and the suction head (energy) of existing moisture level. The characteristics of the SWCC depend largely on the distribution of moisture in pores, soil texture and gradation (Fredlund et al., 2012 as cited in Salour, 2015). The SWCC model in Figure 2-4 indicates that finer soil materials (high PI) has greater suction head compared to coarse gained soil materials. Although there are a number of ways to develop the SWCC of any particular soil material however, it can be estimated from the grain size distribution curves, grain size, packing of the materials and the plasticity index (Salour, 2015; Roberson & Siekmeier, 2009).

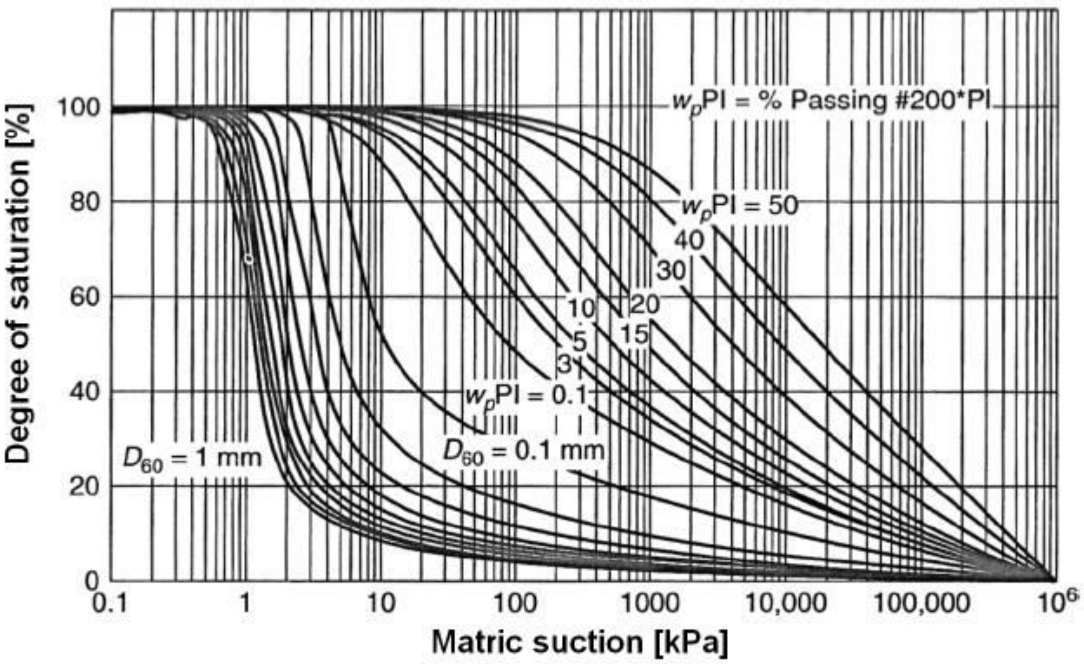


Figure 2-4 SWCC for the Plastic and Non-Plastic Soil Material
(Zapata, 1999 as cited in Salour, 2015)

Uncontrolled vegetation and unsealed shoulder have a direct impact on moisture content and frequently cause pavement distress like edge-break and rutting in the outer wheel path (Matintupa & Tuisku, 2010). In addition pavements constructed in cut-and-fill and box cut areas or beside a hill and large streams, frequently have moisture induced distresses compared to pavements constructed on flat or rolling ground (Ekblad & Isacsson, 2006). In order to understand the mechanism of moisture damage in road pavements, two major types of flexible pavement available in New Zealand, are taken into consideration. Therefore, the effects of excess moisture in the asphalt and the granular pavements are presented in the following sections.

2.2.1 Moisture in Asphalt Pavement

The asphalt pavements used in urban areas and in high volume roads are composed of a thick asphalt concrete surface layer, base course layer and occasional subbase layer. The base course of this pavement is a bound or unbound layer of good quality stones mixed with fines. Often cement, lime and foamed bitumen are used as the binding and stabilising agent between the aggregate and the fines. In order to reduce the stress on the subgrade often an unbound subbase layer of large stone is provided. The asphalt surfacing carries a major portion of the load from the traffic and theoretically provides a smooth, durable, quite riding surface for the traffic (Austroads, 2008a, Mallick & El-Korchi, 2009).

The literature on moisture damage in road pavements is varied and mostly concentrated on the development of pavement distresses including the moisture susceptibility of the different pavement materials and the development of the laboratory and in-situ tests to identify the effect of moisture on asphalt surfaces. Pavement distresses on the asphalt surface layer have been investigated and various laboratory and field based testing methods have been presented for identifying the mechanism of moisture damage in this layer. The reductions of cohesive bond of the binder and adhesive strength of the aggregate-binder mastic have been identified as the cause of major pavement distresses (stripping, potholes). The presence of excess or trapped moisture in road pavements, especially in hot mix asphalt layers, affects it in a series of complex ways. The extent and mechanism of moisture damages in road pavements are complicated and duly received attention among researchers. Moisture damage includes the loss of strength (both cohesive and adhesive), durability, stiffness and finally the disruption of serviceability of the road pavement. Excess moisture in road pavements causes adhesive failure at the aggregate-binder interface and the cohesive failure within the asphalt or aggregate-binder mastic (Airey & Choi, 2002; Bae, Stoffels, Antle, & Lee, 2008). The reduction of adhesion between binder and aggregate, causes stripping and the cohesive failure reduces the stiffness of the pavement layers. Both adhesive and cohesive failures are attributed to moisture damage in road pavements (Hicks, Santucci & Aschenbrener, 2003).

Moisture present on the asphalt surface impairs the bond at the interface of the aggregate-bitumen in the road pavement (Castaneda, Such, & Hammoum, 2004). In general, moisture entering the top sealed layer needs to be carefully controlled. This is because moisture might be trapped in the pavement layer where the air voids are high along with a higher density material on top of the layer beneath. Thus the increase in pore water pressure detaches the aggregate from the binder due to their differential thermal expansion. Besides, moisture in the void areas develops a thin film surrounding the aggregate and consequently reduces the cohesive and adhesive strength of binder materials (Lottman, 1982; Hicks, 1991). In addition, moisture flowing through the voids due to traffic load, imparts severe damage to the pavement. The stresses induced from traffic, trigger the pore water pressure in the pavement and cause failure of the bitumen-aggregate layers (Kandhal, 1992; Thom, 2008). The susceptibility of the asphalt pavement layer to moisture is important in countries where it comprises the majority of flexible road pavements. In New Zealand, the majority of flexible road pavements are granular pavements with a chip seal or thin asphalt surface layer. Therefore, the mechanism of moisture damage in granular flexible pavements is described in the next section.

2.2.2 Moisture in Granular Pavements

This type of flexible pavement is composed of a thin surfacing (asphalt or chipseal), bound or unbound pavement layer (base course and subbase) and the subgrade. The pavement layer carries the major load from the traffic and the surface layer is to provide the required skid resistance, and improves the ride quality. The unbound gravel roads are used in rural areas with low traffic volume. Whereas road pavement (bound) treated with cement, lime or foamed bitumen is used as the base course layer in rural roads with moderate to high traffic (Austroads, 2008a; Transit New Zealand, 2005).

The effects of moisture on road pavements are significant in Australasia, specifically in New Zealand, where mostly thin unbound granular pavements are used on major rural highways with low to moderate amount of traffic (Werkmeister, Dawson & Wellner, 2004). Moisture in road pavements has been considered as a potential threat for performance, durability and serviceability of roads in all countries; especially in New Zealand given the geology, climate and pavement types. Here, major rural highways could be considered as low volume roads. These roads are composed of granular materials (bound and unbound) with a chip seal or thin asphalt layer (Cho & Bahia, 2010; Werkmeister et al., 2006). Theoretically the chip seal layer has to prevent water from penetrating the granular base-course layer. The granular base-course is designed to distribute the load from the traffic, in order to protect the subgrade from deformation and rutting failure. The intrusion of water into the granular base-course or subgrade may cause severe distress and thus hamper the serviceability of the roads (Arnold, Werkmeister & Morkel, 2010; Hussain et al., 2011). Unbound granular materials under soaked or saturated conditions showed poor performance in both the field and laboratory tests. The strength and stiffness of unbound granular pavement layers reduce significantly at or close to the saturation level (Chen, 2007; Dodds et al., 1999; Transit New Zealand, 2000). The effect of moisture on granular pavements is a concern among the practitioners in pavement design and rehabilitation in New Zealand.

The moisture damage mechanism is complex and it requires an understanding of the stages of its development. The presence of a certain amount of moisture in an unbound granular base layer has some positive effect on its strength and stiffness. This unbound granular layer gains strength due to an increase in moisture level till a certain level of saturation is attained (Lekarp, Isacsson & Dawson, 2000). In the mechanistic-empirical method, the unbound granular base layer is designed to attain an equilibrium moisture level before it reaches saturation (Austroads, 2008c). While the moisture level increases towards saturation, excessive pore water pressure develops that reduce the strength and the stiffness of the base course layer. In summary, an amalgamation of these factors such as high degree of saturation and low permeability due to poor drainage, leads to increased pore water pressure and low effective stress of materials, consequently, reducing stiffness and causing deterioration of unbound granular base layers (Lekarp et al., 2000). Excessive moisture in the unbound granular pavement layer, causes permanent deformation due to shear failure, and eventually induces a number of structural (rutting, breaks in the joint) failures in road pavements. In this regard the next section describes the identification of critical pavement distresses for any particular network, or situations (combination of subgrade, traffic, moisture level and weather).

2.3 Moisture and Related Distresses in Road Pavements

Road pavements are exposed to frequent dry and wet conditions due to seasonal variation of moisture. The strength and stiffness of granular base and sub-base layers in road pavements have been found to vary with changes in moisture content (Reid, Crabb, Temporal & Clark, 2006). The following moisture related distresses are prevalent in New Zealand roads that are constructed either as bound or unbound granular layers.

Rutting: Rutting refers to the permanent deformation along the wheel path due to the initial densification of lower pavement layers or shear deformation of upper layers or, permanent strain on the subgrade (Austroads, 2008b). In pavement management systems, rutting is used as one of the performance indicators for flexible pavements, especially in the mechanistic-empirical design procedure. Vertical compressive strain on the subgrade of 20 mm rut depth is considered to be the critical failure value (Henning et al., 2009). Structural overloading and ingression of water through pavement surfaces are the major reasons for accelerated rutting in road pavements. For this reason, the outer lanes used by heavy and slow moving vehicles and areas close to the shoulder show the presence of excessive rutting compared to elsewhere (Henning, Dunn, Costello & Parkman, 2009). Although ingression of water is one of the causes of rutting increased rut depth on road pavements increases the risk of hydroplaning. Therefore, rutting is often treated as a network performance indicator and most pavement management systems adopted it as criteria for triggering maintenance work (Henning et al., 2009).

Stripping: Stripping in road pavement indicates the loosening of binder agent, mineral aggregate and fines in the mastic of the asphalt layer. Overall the combination of inappropriate mix design, low binder content and excessive moisture in voids, excessive fines are responsible for stripping of the road pavement (Austroads, 2009;

Horak & Emery, 2010). Stripping is one of the major distresses caused by moisture in road pavements of New Zealand. Major chip seal roads in New Zealand suffer from stripping of the stone chips along the wheel path. Often potholes on road pavements are caused from stripping within the layers (Transit New Zealand, 2005). Both stripping and potholes hamper the level of serviceability of the roads and usually deteriorates road roughness (Hicks, 1991).

Shoving (plastic flow) and Pumping of Moisture: This form of deformation on road surfaces is observed in areas where there are higher stresses and often inundated with water. Excessive moisture deteriorates the bonding among the pavement layers and causes bulging and horizontal flow of the asphalt surface (Austroads, 2009). Pumping of water on road surfaces is frequently observed on road surfaces in cut and box cut areas. Water from a high ground water table, or side hill areas, have been found to be pumped on road surfaces causing segregation of binder and aggregates. Stripping, loss of serviceability, potholes, flushing and finally premature failure, are the consequences of this form of pumping and shoving of road surfaces (Patrick & Mclarin, 1998; Hicks, 1991).

Cracking: Various forms of cracking such as longitudinal, transverse, diagonal, meandering, block, and alligator are found in road pavements. These hamper a road’s serviceability and often refer to the end of design life of road pavements. In addition to a number of reasons, excessive moisture in the road pavement can be one of the reasons of cracking of road surface layers. Once the road surface is cracked, it becomes vulnerable due to intrusion of moisture through the cracks causing base course and subgrade failure. The presence of irreparable cracking increases road roughness which is used as a performance indicator in pavement management (Austroads, 2009; Heydinger, 2003; Horak & Emery, 2010).

These forms of pavement distresses or damages caused by excessive moisture have significant implications on road asset management. For that reason, road controlling authorities have incorporated various approaches for monitoring and evaluation of moisture damage in road pavements (Chen, Chen, Scullion, & Bilyeu, 2006). In addition the availability and the selection criteria of locally available pavement materials that can counteract the adverse effects of moisture is also a concern for the practitioners (Emery et al., 2007). As it is not always feasible to prevent moisture damages in road pavements, the authorities prefer to implement strategies that could forecast remedial actions against premature failure, and reduce the risk of expensive maintenance or rehabilitation (Halim, Dalziel, Whiteley-Lagace, Moore, & Andoga, 2010). In this perspective, some approaches for evaluating the moisture damages in road pavement are mentioned in section 2.4.

2.4 Approaches for Evaluation of Moisture Damages in Road Pavement

Pavement distresses due to moisture damage are common in road network maintenance; however, early prediction of these can reduce the risk of premature failure. Often researchers follow certain approaches for evaluating the moisture damage potential in road pavements. These approaches vary significantly based on their methods, timeframe, scope, reliability and repeatability (Chen & Scullion, 2008; Gendreau & Soriano, 1998). Although a number of approaches have been observed during the literature review, the following Long Term Pavement Performance (LTPP) and forensic investigation approaches have been described because of their abundance and relevance to research on moisture damage.

2.4.1 Long Term Pavement Performance (LTPP) Appraisal

LTPP appraisal of road pavements is a favoured approach among the road controlling authorities around the world. LTPP studies conducted under the Strategic Highway Research Programme (SHRP) in the USA are the pioneer of long term monitoring and evaluation of road pavements (Rohde, Pinard & Sadzik, 1997; Ovik, Brigisson & Newcomb, 1999). LTPP studies are conducted in Australia, New Zealand and South Africa over the last decade and have been continued as part of the long term monitoring and evaluation of road networks. In New Zealand, LTPP sites were established in 2000 and expanded in 2003 to a total of 140 sites across the country (NZTA, 2012a; Henning et al, 2004).

This form of long term evaluation of road pavements includes establishment of a number of representative road sections for regular tests and measurement. These road sections, often called trial sites, are equipped for monitoring temperature, precipitation, pavement moisture, and ground water table levels in the pavements. In addition, regular inspections and tests are conducted for acquiring the data for roughness, texture, skid resistance, rutting, cracking, and pavement deflections etc. Overall, the objective of the LTPP study is to create a comprehensive database for monitoring and evaluation of pavement performance (Heydinger, 2003; Rohde et al., 1997). The long term objective of this LTPP database is to develop and calibrate the deterioration models for various pavement distresses. These models were developed based on long term databases for a specific weather, pavement, and traffic. Therefore, these models need calibration through the local LTPP database for increased confidence in the prediction of pavement deterioration (Henning et al., 2004; NZTA, 2012a).

The recent NZTA study for suggesting moisture condition guidelines on pavement design by Arampamoorthy and Patrick (2010) is based on the data obtained from New Zealand's LTPP programme. The method adopted by Parera et al. (2004), as cited in Arampamoorthy and Patrick (2010), was suggested for measuring the moisture conditions of the base course materials. In addition, equilibrium moisture content of 60% for base course and a saturated condition for subgrade has been recommended based on laboratory assessment of LTPP's pavement materials. However, this study overlooked the changes in structural capacity of pavement layers due to changes in moisture content (Arampamoorthy & Patrick, 2010).

In a similar study, for formulating a new approach for modelling 'rutting' based on New Zealand's LTPP and Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF) test data, Henning et al., (2009) stated the significance of field conditions, especially the intrusion of moisture through cracks and poor drainage for predicting the distresses in road pavements. The significance of actual weather and precipitation on road pavements instead of built-in or constant environmental conditions is also reiterated in Werkmeister et al. (2004). This study emphasised the changes in pavement layer properties due to variation in seasonal moisture content. Results from CAPTIF test data indicates that use of subgrade strain for predicting pavement remaining life is not feasible, rather a new relation was suggested for predicting pavement remaining life from FWD central deflections (Werkmeister et al., 2004).

2.4.2 Forensic Investigation

Forensic investigations through destructive or non-destructive tests are preferred in the literature. However, the combination of both the laboratory and in-situ tests represents a holistic approach. Several researches have indicated the acceptability and suitability of both in-situ tests, using GPR and FWD, and conducting laboratory based Triaxial or Dynamic modulus tests in forensic investigation (Benedetto & Pensa, 2007; Chen, 2007; Gidel, Hornych, Chauvarn, Breysse & Denis, 2001). These forms of forensic investigation using both the field and laboratory based testing have been utilised effectively for moisture damage assessment in road pavements (Chen et al, 2006; Heydinger & Davies, 2006).

Forensic investigation was adopted for investigating pavement premature failures and early detection of distresses (Chen et al., 2006). The scope of forensic investigation for early detection or investigation of premature distresses in road pavements is widely supported by the literature. There have been a number of studies that uses forensic investigation of road pavements, especially in identifying the causes of premature distresses (Alderson, 2006; Benedetto & Pensa, 2007; Chen et al, 2006; Chen, 2007; Chen & Scullion, 2008; Chen, Hong

& Zhou, 2011b; Chen, Scullion & Lee, 2012; Donovan & Tutumler, 2009, Horak & Emery 2010). In addition, forensic investigation in terms of in-situ tests are widely used as a tool for performance evaluation at the post-construction stage and also for predicting distresses in road pavements (Alam et al., 2007; Benedetto & Pensa, 2007; Kavussi, Rafiei &Yasrobi, 2010; Saltan & Terzi, 2008). Overall the literature on forensic investigations, relevant to this research, falls into three groups. Some of the studies dealt with mostly laboratory tests for identifying the causes of distresses. Other studies have been found using in-situ tests for the investigation. However, combining both the in-situ and laboratory tests for forensic investigation in road pavements is found in the literature and can be considered effective for identifying the cause and effect of most distresses. In the next sections, the above three categories of studies are summarised briefly for assessing their relevance for this particular research.

2.4.3 Destructive and Laboratory Based Tests

A number of destructive and laboratory tests can be used for identifying the moisture susceptibility of road pavements. It has been a challenge for researchers to identify the appropriate tests for measuring the moisture susceptibility of road pavements (Breakah, Bausano & Williams, 2009). Several studies have indicated the applicability of the Modified Lottman test, and Dynamic modulus test for measuring moisture susceptibility of asphalt pavements (Breakah et al., 2009; Huang et al., 2008). The modified Lottman test (AASHTO T283) measures the Tensile Strength Ratio (TSR) and has been used for reporting the moisture sensitivity of pavement layers. Two sets of cylindrical specimens of bituminous mixtures (100 mm diameter by 63.5 mm high) with fixed air voids (7 ± 1%), are compacted by the Superpave gyratory compactor. Among them, the dry samples are considered as control specimens and others are moisture conditioned (up to 70-80%). These samples are conditioned for about 16 hours in a freezer at -18^{0}C and about 24 hours in a thaw cycle at 60^{0}C. Both groups of samples are then subjected to indirect tensile loading at a rate of 50 mm/min at 25^{0}C. The TSR is determined from the ratio of peak loads of the moisture conditioned and dry bituminous specimens. Usually the range of TSR from 0.70 to 0.80 is recommended by the road management authorities (Breakah et al., 2009; Huang et al., 2008).

The dynamic modulus test (ASTM D3497) measures the dynamic complex modulus (E^*), defined as the ratio of maximum dynamic stress to the recoverable axial strain. The test includes the application of sinusoidal compressive stress along with different frequency and temperatures for detecting the visco-elastic properties of bituminous mixtures. A high dynamic modulus often represents the relative stiffness and resistance against rutting at different temperatures (Breakah et al., 2009).

Although both of the tests are widely utilised for identifying the moisture susceptibility of road pavements, research indicates that the dynamic modulus test has certain advantages over the modified Lottman test. The modified Lottman test provides the TSR value which helps in minimising the problem. Dynamic modulus testing is widely accepted for evaluating the moisture susceptibility of road pavement mixes. It includes the visco-elastic properties of the mixes and a range of temperatures which are ideal for predicting road pavement distresses. It is feasible to simulate the results obtained in the dynamic modulus test using the concept of mechanistic-empirical design for road pavements for predicting rutting, and related failures (Solaimanian et al., 2007 and Kim et al., 2003 as cited in Breakah et al., 2009).

The effect of moisture on asphalt mixes can be evaluated by means of the crack-growth index and the change in fatigue life parameters. The crack-growth index is measured by applying the visco-elastic fracture model, where the cyclic load is applied for failure (Caro, Beltran, Alvarez & Estakhri, 2012). In this study, Caro et al., (2012) conducted relaxation modulus and dynamic mechanical analyser tests with Dynamic Shear Rheometer (TA-series AR 2000) for measuring the input parameters for formulating the visco-elastic fracture model. The moisture damage ratio and the retained fatigue life are the outputs of the visco-elastic fracture model, which has been used for quantifying the moisture susceptibility. Here moisture damage ratio is calculated by dividing the crack growth index of wet and dry specimens. A moisture damage ratio of greater than 1.0 indicates the presence of excessive cracks in the wet specimen compared to the dry one. The retained fatigue life (R.F.) can be calculated by the Equation 2-1.

$$\mathbf{R.F. = (N_{fwet} / N_{fdry})\ 100\%,} \quad \textbf{Equation 2-1}$$

Where, N_{fwet}= Fatigue life in dry condition, N_{fdry} = Fatigue life in wet condition Generally the higher value of R.F. for any specimen indicates the higher resistance of the materials against moisture damage (Caro et al., 2012).

It is often critical to simulate the dynamic loading pattern of unbound granular layers in laboratory tests. For this reason, the indirect tensile strength or unconfined compressive strength tests are not suitable for predicting the permanent deformation of granular pavement layers. The dynamic characteristic of loading along with the measurement of both the axial and the radial deformation of the test specimens is measured in the repeated load triaxial test. This test could predict the characteristics of permanent deformation of unbound granular pavement layers (Gidel et al., 2001; Hunter et al., 2009). Permanent deformation characteristics of granular pavement layers are significant for predicting the rutting of road pavements. Rutting of road pavements is considered as the critical pavement distress as this necessarily induces the moisture damage and also reduces the level of service due to increased moisture film thickness on road pavements. The relationship between the permanent deformation or induced plastic strain and stress is also dependent on the moisture level of the test specimen which can be controlled for verifying the impact of moisture on road pavements (Gidel et al., 2001; Ekblad & Isacsson, 2008).

Another common laboratory based test is the permeability test that can measure the rate of flow of water through any particular materials. This test is utilised for hydraulic analysis during embankment design especially for evaluating the stability of side slope. The constant head permeability test is widely utilised to identify the flow of water through materials used as backfill for abutments, under drains and also for sand blanket used in sand drains. Another common use of the test is to compare the permeability of the two types of soil or materials and for the studies related to drainage and settlement of foundation soils. This permeability test is applicable for materials which have a coefficient of permeability of approximately 300 mm/day. The testing is done in laboratory environment therefore need to be corrected for temperature (CDOT, 1998).

2.4.4 Non-Destructive and In-Situ Test Methods

Ground Penetrating Radar (GPR) is a non-destructive, in-situ, testing equipment that can be effectively used for detecting the presence of moisture in road pavements. A number of studies have been conducted to verify the applicability of GPR for measurement of unsaturated soil moisture in road pavements (Benedetto, 2010; Benedetto & Pensa, 2007). Both ground and air coupled GPR antennas can monitor the moisture content in the pavement layer from the relationship between the frequency modulation of the electromagnetic waves (propagated from GPR senders) and the volumetric moisture content (Benedetto, 20101). Figure 2-5 indicates the relationship between the changes in frequency of electromagnetic waves with the changes in moisture content. The frequency of the propagated waves from a GPR reduces due to increase in volumetric moisture content. However, the GPR technique is an expensive, rigorous process and requires further study to improve its reliability in in-situ detection of moisture in road pavements (Benedetto & Pensa, 2007).

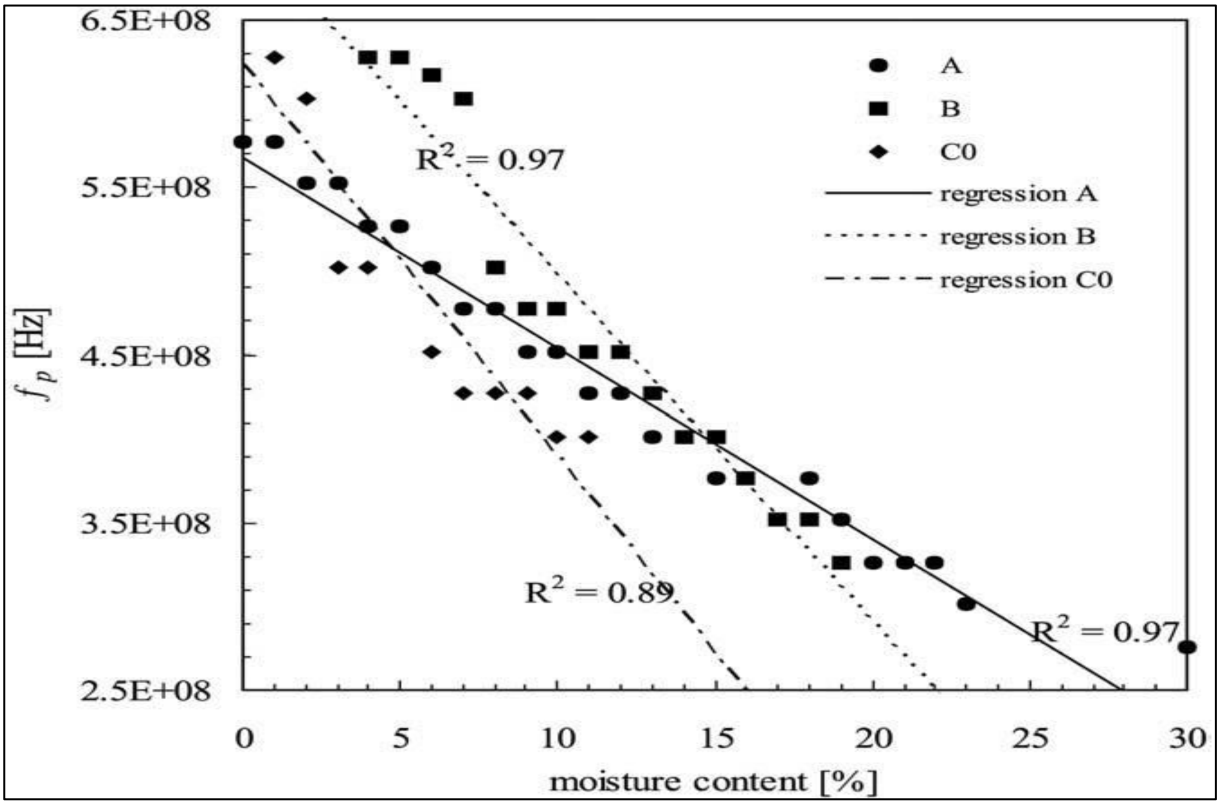


Figure 2-5 Relationship between the Changes in Moisture and Frequency of Propagated wave in GPR Technology (Benedetto, 2010)

Another commonly used apparatus for in-situ evaluation of pavement layers is the Dynamic Cone Penetrometer (DCP). Although it is a destructive technique, the relative size of the core holes compared to a test pit makes it popular for assessment of pavement layer strength for small projects and as a tool for quality assessment. The DCP is a simple tool with a cone at the end of a rod and the cone is inserted into the pavement by the impulse force from a falling weight. Here the rate of penetration into the pavement is counted (in mm/blow) and correlated with the equivalent CBR of the layers. DCP can be used to obtain a relatively good indication of the CBR of the subgrade material. It also generates a relative measure of the strength along with the profile of the pavement layers and is often preferred as a speedy and inexpensive assessment of road assets (ASTM, 2009; Thom, 2008).

Real time measurement of moisture by Time Domain Reflectometer (TDR) probe has increased the acceptability of the research on moisture damage on road pavements. The TDR probe has been used for a number of studies to successfully identify the level and flow of moisture through different layers in road pavements (Ekblad & Isacsson, 2008; Hussain et al., 2011). Ekblad and Isacsson (2006) used the TDR probe for measuring the real time water movement in laboratory prepared 500 mm diameter and 1000 mm long cylindrical specimens of coarse granular pavement materials. On the other hand, Hussain et al., (2011) used TDR probe for monitoring the relative vertical and horizontal flow of water in a 60 m long and 4 m wide test track in Canterbury, New Zealand. Both of these studies were successful in monitoring the flow of water in granular materials in two different (laboratory and test track) test facilities. This necessarily indicates the suitability of the TDR probe for monitoring the field moisture movement in actual road pavements.

In general, there are various in-situ tests widely used for evaluation of road pavements. Broadly these tests are either destructive or non-destructive in nature; however, in-situ tests without disturbing the road pavement are always preferable. Although the cores or trenches are reinstated, it is practically difficult for attaining a similar strength to the surrounding pavement and they often deform to create potholes. Therefore, pavement practitioners often prefer non-destructive in-situ tests along with laboratory tests for cross evaluation of both types of test for any form of evaluation. In this respect, the following section briefly discusses forensic investigation based on combining both the in-situ and laboratory tests.

2.4.5 Combination of In-Situ (non-destructive) and Laboratory (destructive) test methods

Forensic investigation including both field tests (non-destructive) and destructive laboratory tests have been used successfully for evaluating road pavement layers and identifying the reasons for pavement distresses (Chen, 2007; Chen, Chang & Fu, 2011a; Chen et al., 2006; Chen et al., 2006; Chen & Scullion, 2008). Most of these studies combined both destructive and non-destructive tests for detecting causes of premature failure in road pavements and also for identification of suitable remedies. Research using both in-situ non-destructive tests and destructive laboratory tests has been found to be successful in detecting moisture susceptibility of road base course material. In the course of investigating the premature failure in a temporary detour of an interstate highway in Austin, Texas, Chen et al., (2006) conducted a forensic investigation using GPR, FWD and a number of laboratory tests such as permanent deformation, resilient modulus, permeability, and repeated load tri-axial tests. In this study, GPR was effectively used to locate the suitable location of trenching and coring for further investigation. In addition, FWD deflections obtained from the investigation showed the improvement of pavement performance after the treatment as presented in Figure 2-6.

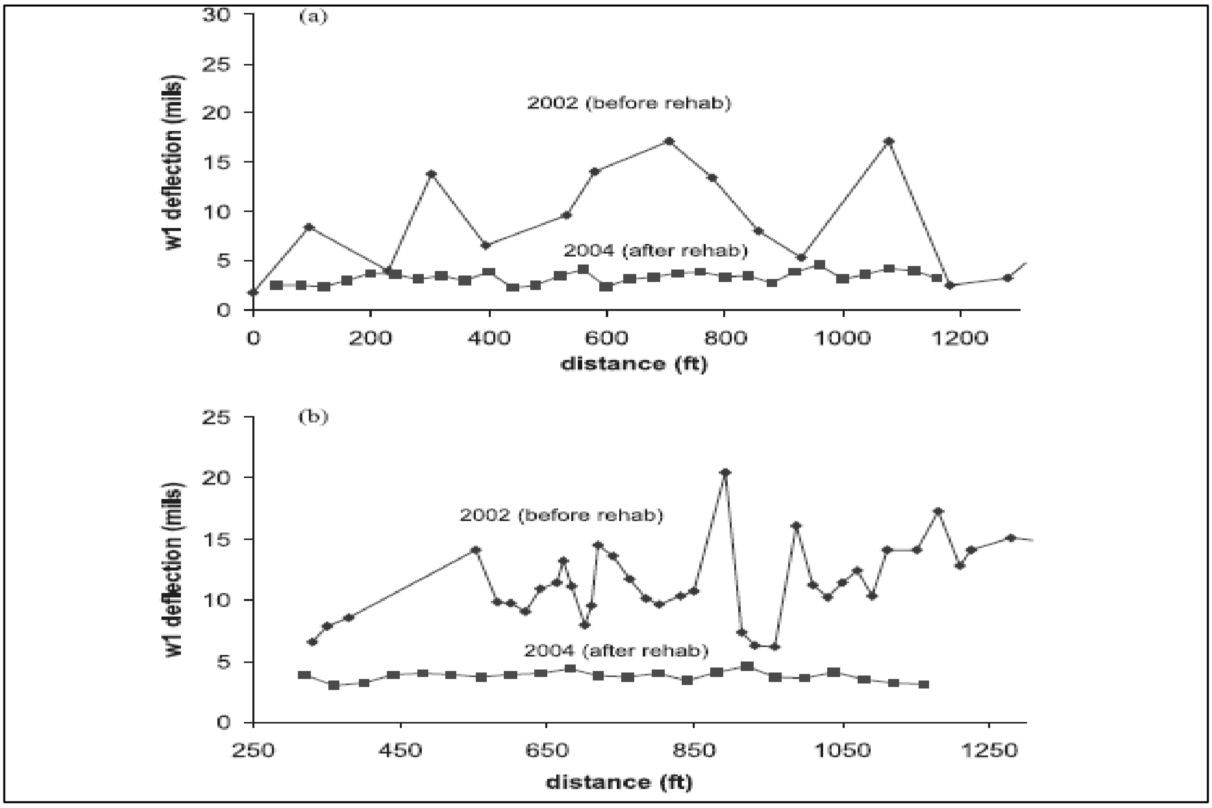


Figure 2-6 Comparison of Peak FWD deflections (40 KN load) before and after Rehabilitation (Chen et al., 2006)

Poor quality materials in the base course along with poor construction quality were the reasons for premature failure. The base course material was found to be moisture-susceptible through the tube suction (or dielectric test). High dielectric values measured through the tube suction test indicates moisture susceptibility of base course material and consequent reduced strength and stiffness (Chen et al., 2006). Water entering into the base course through the permeable asphalt surface layer and joints were weakening the materials and caused severe deformation, rutting and potholes. The FWD deflection test result shown in Figure 2-6 indicates the improvement of strength after a major rehabilitation with improved base course material and asphalt surfacing (Chen et al., 2006).

In Chen (2007), an excessively brittle base material was found as the root cause of severe premature cracking in a road after just two years of construction. GPR, FWD, Geo-gauge and portable FWD were used for initial assessment and nuclear density gauge, DCP and other laboratory based forensic investigation were successful in identifying the causes of the premature cracking. The base course was stabilised with lime and without a sufficient mellowing period there was excessive shrinkage that caused the premature cracking. The newly constructed base layer with two day mellowing period worked well and the road pavement surveyed for a year did not show any premature distresses (Chen, 2007). In this perspective, Chen et al., (2011a) reported base layer moduli as a quality control criterion. Generally the degree of compaction and the moisture content have been considered as the quality control tool for the base layer. Forensic studies of a number of premature failure road pavements have shown that the road pavements with either too weak or too brittle base layers have cracks and eventually lead to damage to the surface layers as well (Chen et al, 2011a; Chen, 2007).

Forensic investigation of road pavements is a comprehensive process and often requires the integration of both the in-situ (non-destructive) and laboratory based destructive tests. Non-destructive instruments like GPR, FWD and Geo-gauge were helpful in identifying the contributing factors of moisture damage in road pavements (Chen & Scullion, 2008; Chen et al., 2012). GPR was helpful in identifying the extent of stripping and high porosity in two road pavements and were verified through coring. FWD test data are useful in assessing the strength of the pavement and help in identifying the weak areas due to a wet base or subgrade. A combination of GPR, permeability, repeated load triaxial and tube suction (dielectric) tests were also successful in identifying a weak and moisture-susceptible base layer which eventually causes permanent deformation and rutting failure (Chen & Scullion, 2008). Thus there is scope for a combination of both destructive and non-destructive tests for identification of moisture damage in road pavements. Among them the non-destructive FWD tests are widely utilised for performance measurement, construction quality assessment and evaluation of strength of road pavements. The application of deflection tests in road pavements is presented in section 2.5.

2.5 Application of Deflection Tests on Road Pavements

2.5.1 Deflection Testing Equipment

Deflection measurement of pavements in response to an applied load is widely utilised as a non-destructive and non-intrusive technique for evaluation of the structural capacity of pavements ranging from unpaved roads to airfield runways. This non-destructive technique for evaluation of road pavements has been in practice since the 1950s. The output of the deflection test in the form of the deflection bowl has been extensively used in the mechanistic-empirical approach for pavement design and rehabilitation (Arnold et al., 2009; Rada & Nazarian, 2011; Weligamage, Piyatrapoomi & Gunapala, 2010). Deflection measurement equipment for road pavements has evolved significantly. From the Benkelman Beam used in the 1950s to the present traffic speed deflectometer, these devices have been used extensively for effective, speedy, reliable, repeatable and real time evaluation of road pavements around the world (Rasmussen et al., 2002; Rada & Nazarian, 2011). The Table 2-1 summarises the deflection measurement devices or technologies used for evaluation of road pavements.

Table 2-1 Deflection Testing Devices used for Road Pavements

No	Deflection testing equipment
01	**Benkelman beam:** This oldest device has been in use since the 1950s and was effective in reporting the bearing capacity of roads based on the deflection pattern due to a concentrated heavy vehicle wheel load.
02	**Deflectograph:** Advanced vehicle mounted deflection device that works based on the Benkelman beam principle. This slow moving device collects deflection patterns from two Benkelman beams placed under the rear axle wheel path.
03	**Falling Weight Deflectometer (FWD):** This deflection measuring device uses a dynamic impulse load and records pavement responses by geophones at various points on the pavement. It generates a deflection bowl for each test location and the central deflection along with the radius of curvature of the bowl can effectively indicate the strength of various pavement layers. The Light Weight Deflectometer (LWD) and Heavy Weight Deflectometer (HWD) are different from FWD due to their use and applied load. LWD is a static single point load and suitable as a quality assessment tool in low volume roads. Whereas the HWD used an equivalent load of modern commercial aircraft and used for deflection measurement in airfield pavements.
04	**High Speed/ Traffic Speed Deflectometer:** These versions of the deflectometer have evolved for continuous monitoring or assessment of network wide road pavements. These devices measure the speed of pavement vertical deflections by Doppler laser sensors and calculate the deflections at various points of the deflection bowl. These devices have the added advantage that they can measure the deflections at traffic speed and do not require stopping and traffic control.
05	Others devices used in various countries are: • Rolling weight deflectometer • Rolling dynamic deflectometer • Rolling wheel deflectometer • High speed deflectograph

Source: (Rada & Nazarian, 2011; Weligamage et al. 2010)

Among all the devices used for deflection measurement in road pavements, the FWD is most popular and widely utilised in many countries for evaluation of both of pavement performance and strength. A brief outline of the FWD and its applications are presented in the following sections.

In general the FWD measures deflections at a series of points in road pavements in response to a dynamic impulse load for replicating the loads from a moving vehicle. The vertical deformation or deflection of road pavements due to the applied load is collected by a series of geophone sensors. Usually seven geophone sensors are placed at 25 cm apart, receive the responses from the loads and, on that basis, infer a deflection basin (TxDOT, 2008) as showed in Figure 2-7.

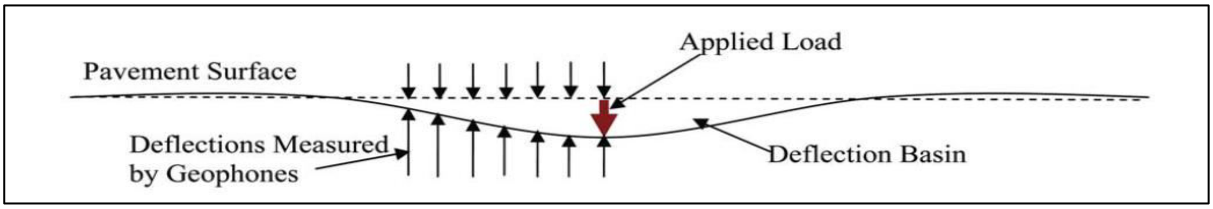


Figure 2-7 Typical Shape of a Deflection Bowl Obtained from FWD Test

The deflection basin/bowl (Figure 2-7) obtained from the FWD test can be utilised for extracting the layer properties, predicting remaining life and verifying the construction quality of the road pavement. The pavement responses towards FWD loading are mainly dependent on different layer strength, stiffness and thickness. The layer properties such as resilient modulus and structural number of a pavement can be identified through back calculation of FWD test data (Grenier & Konrad, 2009; Horak, 2007; Sharma & Das, 2008). Generally the central deflection and curvature of the deflection bowls (Figure 2-7) obtained from the FWD tests are analysed through back-calculation for evaluation of pavement layer strength. The overall shape of the deflection bowl, as shown in Figure 2-8, is used for identification of pavement layer stiffness.

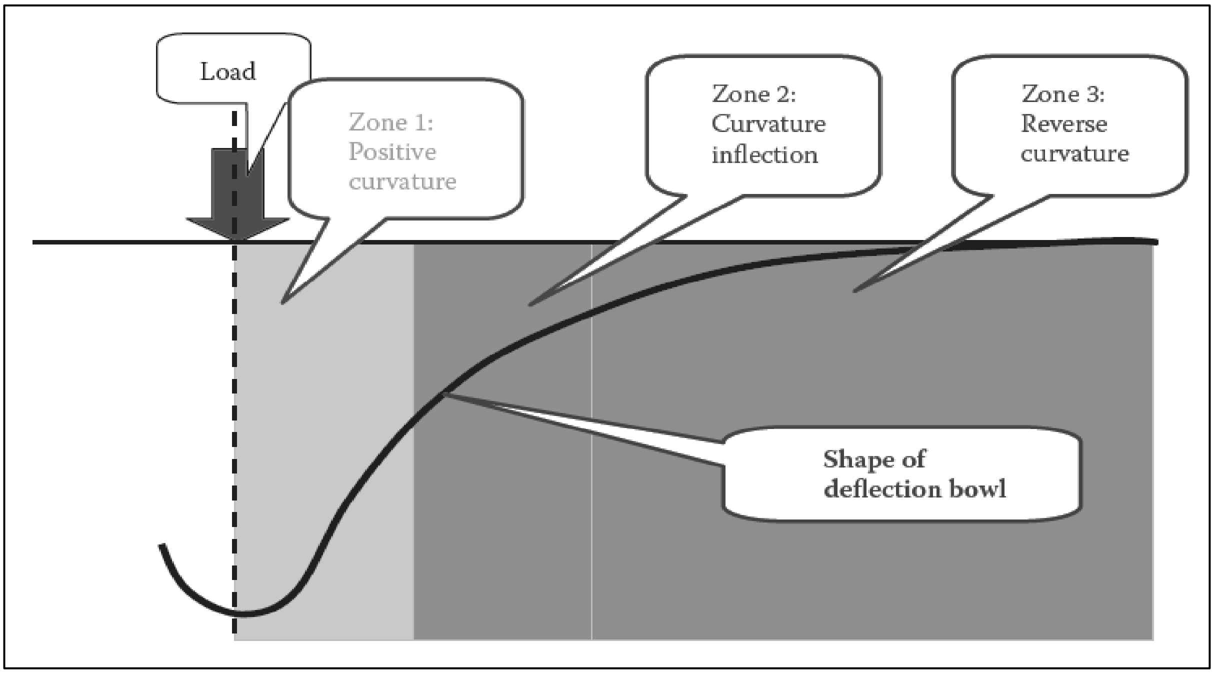


Figure 2-8 Curvature Zones of Deflection Bowl/Basin (Horak, 2007)

The subgrade stiffness is reflected by the shape and curvature of the outer part (zone 3 as shown in Figure 2-8) whereas the central deflection and curvature of the deflection basin at the loading point (zone 1) indicates the stiffness of the surface layer. The middle layer (zone 2) of the deflection bowl in Figure 2-8 represents the stiffness of the base layer. A pavement with weak surface layers along with strong subgrade would generate a deflection bowl of maximum deflection and high curvature around the loading point (Salt & Stevens, 2001; Horak, 2008).

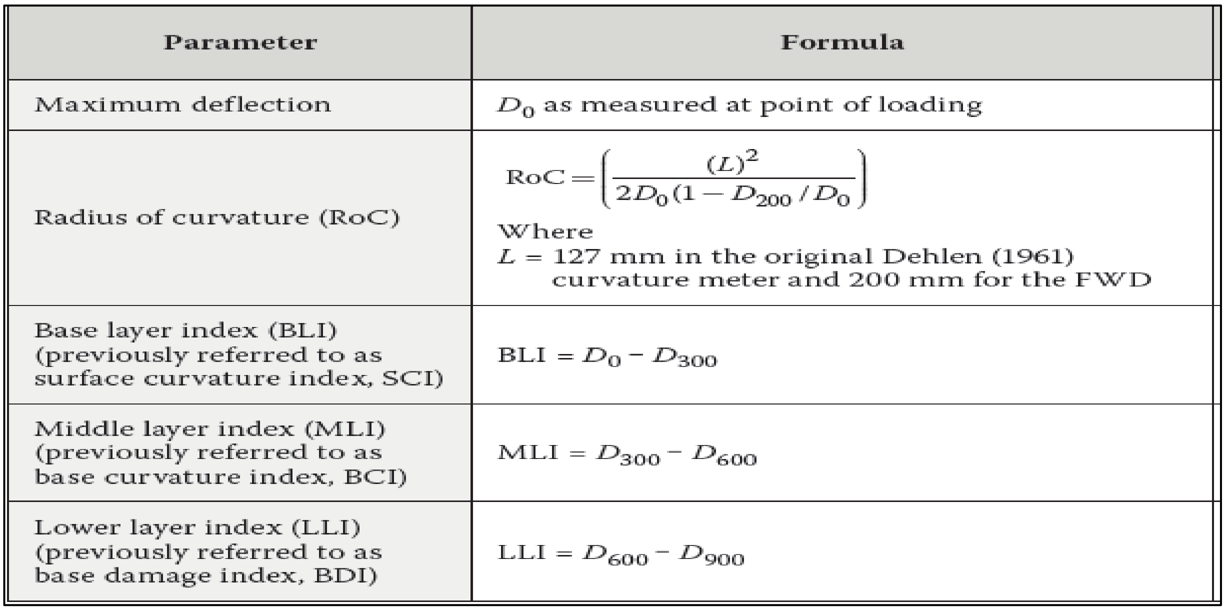
A range of loading can be used at each location and the test sites should include both fair and distressed road pavements. For project level testing a minimum of 30 testing points or 10 points per km in a network can give comprehensive information about the pavement properties. Usually the air and pavement temperature need to be collected during FWD tests and annual calibration is essential for maintaining the integrity of data collection (Arnold et al., 2009; Donovan & Tutumler, 2009).

Several studies have discussed about the comparative advantages of FWD for deflection measurements on road pavements due to its comprehensiveness and sophistication, however, analysing the test data is often found to be rigorous and required careful judgement of experienced engineers or technicians (Horak 2007; Salt & Stevens, 2001; Sharma & Das, 2008). FWD has certain advantages over the earlier versions of deflection measurement equipment such as Benkelman beam and deflectograph due to its robustness and variation of loads (Chen et al., 2006). Development of complex computer programmes has increased the feasibility of using FWD for the complex iterative processes of back calculation for identifying strength of the pavement layers (Grenier & Konrad, 2009; Isaac & Kimberly, 2009). In spite of that, FWD has certain disadvantageous because the test is static, time consuming, expensive and requires extensive traffic control which is often difficult in high speed road networks.

From this perspective, the High Speed Deflectograph (HSD) and Traffic Speed Deflectometer (TSD) could be feasible options instead of the FWD. These devices are suitable for deflection measurement in a high speed road network without expensive and complex traffic control. Recent studies on HSD show promising outcomes in terms of its repeatability, reproducibility, and feasibility for measurement of pavement strength based on the laser Doppler concept at normal traffic speed (Rasmussen et al., 2002). HSD and TSD are the advanced versions of deflection measuring devices used for evaluation of road pavements. These devices apply Doppler-laser technology for providing pavement response to wheel loads. The laser sensors are used for recording the acceleration of the vertical deflection of road pavements due to applied load from moving traffic loads. There is scope for applying these dynamic deflectometer for assessment of road pavements in a network. A number of studies have indicated the applicability of these deflectometer for providing a swift and reliable assessment of the structural condition of road network (Weligamage et al., 2010; Rasmussen et al., 2002). The applicability of HSD and TSD has been verified by the study on Danish road network and results obtained from the research were compared with FWD tests. In addition, recent attempts for assessing the Queensland road network using the TSD has been proved successful for speedy assessment of the structural condition of the road network. It has been found that TSD can provide continuous, repeatable deflection data at traffic speed and the comparison and correlation of the deflections with TSD and FWD tests show promising outcomes. However, TSD cannot collect data in wet condition and there are difficulties reported in processing test data for rough and bumpy roads (Rada & Nazarian, 2011; Weligamage et al., 2010). At this point, the discussions over the wider applications of deflection test are included in the following sections.

2.5.2 Deflection Tests for Pavement Performance Measurement

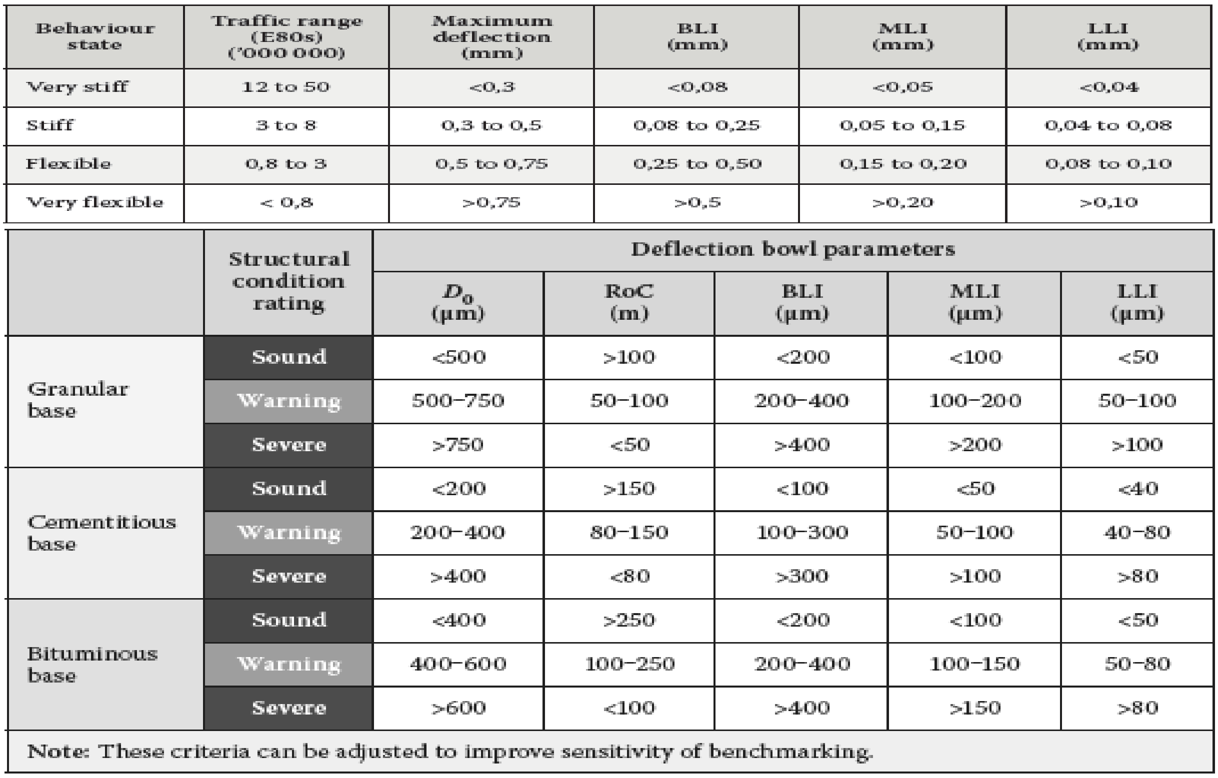
The recent advancement in pavement management systems through long term performance specified maintenance contracts in New Zealand has resulted in the adoption of FWD deflection measurement as a vital tool for performance evaluation (Daly, 2004). The FWD can successfully detect the causes for premature failure and distresses of road pavements (Chen & Scullion, 2008; Elkins et al., 2011). Benchmarking of pavement structural strength based on FWD test data using semi-mechanistic and semi-empirical approaches can be effective for avoiding the complex iterative and potentially erroneous back-calculation process. This approach can be used for development of a framework or guidelines for using FWD as a tool for performance indicators of road pavements. In Horak (2008), a semi-mechanistic and empirical benchmarking process for structural evaluation of a pavement's structural strengths was presented. The benchmarking process adopted several parameters (Figure 2-9) based on the deflection bowl shape and deflection data at various points on the pavement.



Parameter	Formula
Maximum deflection	D_0 as measured at point of loading
Radius of curvature (RoC)	$\text{RoC} = \left(\frac{(L)^2}{2D_0(1 - D_{200} / D_0} \right)$ Where L = 127 mm in the original Dehlen (1961) curvature meter and 200 mm for the FWD
Base layer index (BLI) (previously referred to as surface curvature index, SCI)	$\text{BLI} = D_0 - D_{300}$
Middle layer index (MLI) (previously referred to as base curvature index, BCI)	$\text{MLI} = D_{300} - D_{600}$
Lower layer index (LLI) (previously referred to as base damage index, BDI)	$\text{LLI} = D_{600} - D_{900}$

Figure 2-9 Deflection Bowl Parameters Used for Benchmarking (Horak, 2008)

Based on the above mentioned parameters of the FWD deflection bowl along with visual and experimental investigation, several criteria (in Figure 2-10) have been developed and applied successfully for evaluation of a number of flexible road pavements in South Africa (Horak, 2007, 2008).



Behaviour state	Traffic range (E80s) ('000 000)	Maximum deflection (mm)	BLI (mm)	MLI (mm)	LLI (mm)
Very stiff	12 to 50	<0,3	<0,08	<0,05	<0,04
Stiff	3 to 8	0,3 to 0,5	0,08 to 0,25	0,05 to 0,15	0,04 to 0,08
Flexible	0,8 to 3	0,5 to 0,75	0,25 to 0,50	0,15 to 0,20	0,08 to 0,10
Very flexible	< 0,8	>0,75	>0,5	>0,20	>0,10

	Structural condition rating	Deflection bowl parameters				
		D_0 (µm)	RoC (m)	BLI (µm)	MLI (µm)	LLI (µm)
Granular base	Sound	<500	>100	<200	<100	<50
	Warning	500–750	50–100	200–400	100–200	50–100
	Severe	>750	<50	>400	>200	>100
Cementitious base	Sound	<200	>150	<100	<50	<40
	Warning	200–400	80–150	100–300	50–100	40–80
	Severe	>400	<80	>300	>100	>80
Bituminous base	Sound	<400	>250	<200	<100	<50
	Warning	400–600	100–250	200–400	100–150	50–80
	Severe	>600	<100	>400	>150	>80

Note: These criteria can be adjusted to improve sensitivity of benchmarking.

Figure 2-10 Criteria for Evaluating Granular Pavements (Horak, 2008)

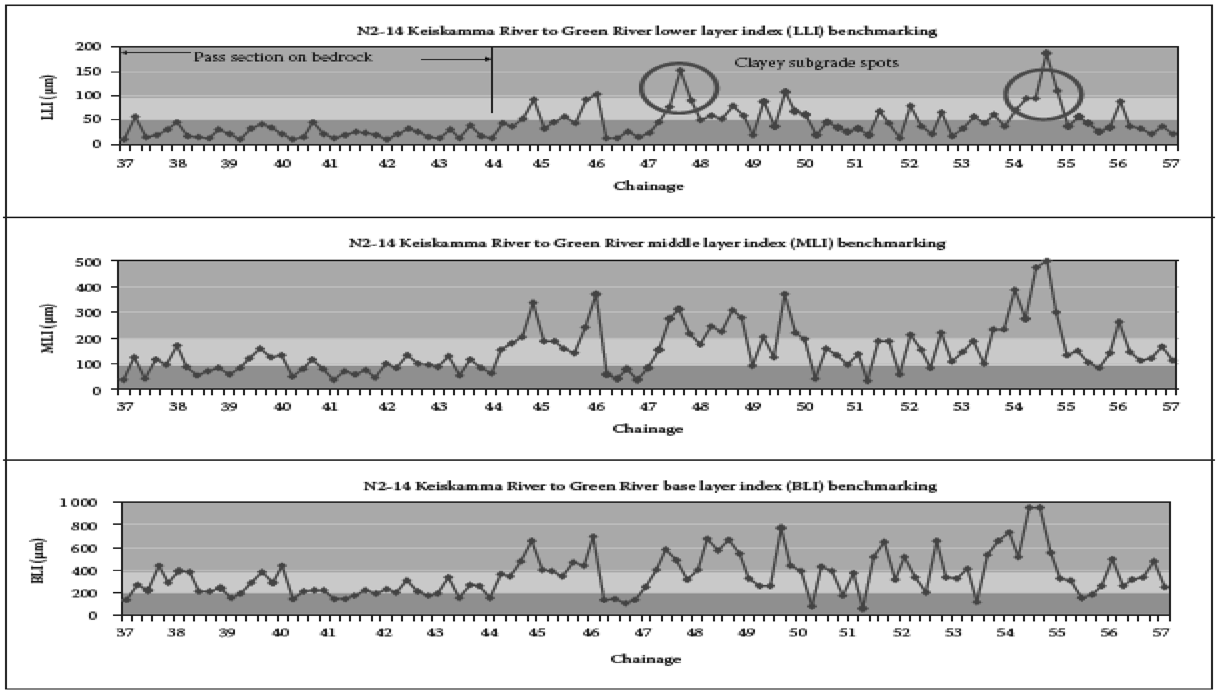


Figure 2-11 Benchmarking using Deflection Bowl Parameters (Horak, 2008)

Horak (2008) developed the framework (in Figure 2-11), based on the above mentioned criteria (Figure 2-10), for evaluating roads or sections of a road network. However, the overall benchmarking processes have to be verified through visual and experimental techniques such as trenching, coring, GPR etc.

Although these forms of empirical indicators have been widely used for pavement performance measurement, improvised performance indicators can be developed from long term FWD deflection data. Jacoby (2008) indicates that critical tensile micro strain ($\mu\varepsilon_T$) at the bottom of the base layer and compressive micro strain ($\mu\varepsilon_C$) at the top of the subgrade can predict pavement performance and failure instead of traditional empirical central deflection (D_0) and curvature (D_0 - D_{200}). Both the tensile and compressive micro strains are estimated considering the FWD deflection data, thickness of the layers and have been found as a sound indicator for predicting rutting and cracking failures (Jacoby, 2008). These forms of benchmarking and structural indicators based on FWD deflection data, can be considered for evaluating the effects of moisture on pavement strength as well.

2.5.3 Deflection Tests for Evaluating Effects of Moisture in Pavement

The effect of moisture in road pavements, specifically on pavement strength, can be measured through deflection tests. A number of studies have been conducted for evaluating the seasonal fluctuations of pavement layer stiffness through in-situ deflection and moisture measurements (Ovik et al., 1999; Berthelot et al., 2008; Heydinger &Davies, 2006; Timm et al., 1998).

Most of these studies were part of the LTPP study incorporated under the SHRP at various state highways in the USA. In SHRP, seasonal monitoring of in-situ moisture, temperature and freeze-thaw cycles was included in the long term performance evaluation of road pavements (Heydinger, 2003; Ovik et al., 1999).

FWD deflection tests along with seasonal monitoring of temperature, moisture content and freeze-thaw cycle, in road pavements have been used successfully in SHRP programmes in the USA. Ovik et al., (1999) conducted a study for quantifying the relationship between the temperature, moisture content, other subsurface conditions and the pavement layer modulus on State Highways in Minnesota. As part of the Minnesota road research project, the study involves on-site weather stations and long term deflection measurements for evaluating the changes in layer stiffness in different seasons. Thermocouples are used for measuring the pavement layer temperature. TDR was used for volumetric moisture measurement and the resistivity probes and moisture blocks measure the depth of frost. The overall outcome of the study reflects that there are fluctuations of pavement layer stiffness due to changes in moisture and temperature in various seasons. Seasonal factors for predicting the changes in layer stiffness have been presented in this study (Ovik et al., 1999). Here the season from September to November had been considered as a baseline and the ratio of back-calculated layer modulus at different seasons to the base season is presented as seasonal factors. Additionally, the asphalt layer modulus affected by temperature is found to be its lowest in summer. The base layer modulus in the spring-thaw period and the subgrade modulus in late spring and summer are found to be at minimum. Overall the base layer and subgrade layer modulus are mostly affected by the moisture content and the freeze-thaw cycle (Ovik et al., 1999).

A similar long term study involving deflection tests for evaluating the seasonal effects on subgrade soil was conducted by Heydinger (2003). This study was part of the Ohio SHRP, which includes seasonal monitoring of moisture, temperature, precipitation, frost depth, and FWD deflection tests. TDR probes are used here as well, for in-situ measurement of moisture. In addition, changes in water table depth are also monitored. Interestingly, no relationship between the precipitation and the volumetric moisture content in TDR probes was found as shown in Figure 2-12.

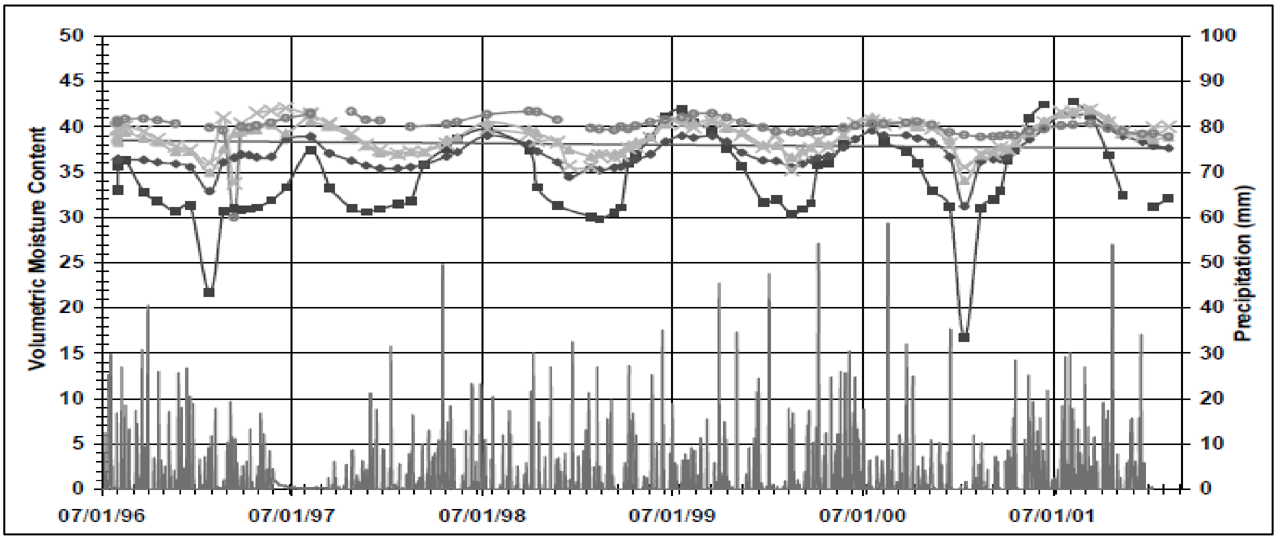


Figure 2-12 Changes in Precipitation and Volumetric Moisture Content (Heydinger, 2003)

In Figure 2-12, the changes in moisture content in pavement layers detected by TDR probes and the changes in precipitation. The resilient modulus of unbound granular materials, as calculated from the FWD deflection tests is found to be affected by the seasonal changes in moisture content. Subgrade modulus is found to decrease with the increase in moisture; however, no relation was developed because both of their properties were material and history dependent. Generally the changes in resilient modulus of the subgrade are higher in wet seasons compared to the dry weather (Heydinger & Davies, 2006).

Usually the road pavement undergoes through a series of strengthening and weakening during the seasonal variations of moisture. This variation is significant in cold regions with the thin flexible pavement (Simonsen and Isacsson, 1999 as cited in Salour, 2015). Figure 2-13 shows the variation of the pavement stiffness due to changes in moisture and related pore water pressure in cold regions during freezing and thawing cycle. In cold region, pavement gained strength (stiffness) at winter due to the freezing of the moisture in the bound or unbound layer (as seen in Figure 2-13). The next phase is the structural weakening due to thawing of pavement layer. This is caused due to rise in temperature in the spring. It causes a release of excess moisture in the pavement structure due to the melting of ice. Due to the variation of temperature at the surface and bottom of the pavement, a layer of ice lenses are trapped at the bottom of the pavement which often causes pumping of the fines at this freeze-thaw cycle. This can cause a quick reduction of resilient modulus of the pavement layer. When the temperature increases at summer all the ice melted and excess water is drained out, pavement layer recovered its stiffness (Figure 2-13) (Salour, 2015). Although the freeze-thaw cycles are not predominant in the region where the research has been conducted however, the mechanism of the changes in stiffness of the pavement can be essential in developing the knowledge of the effect of moisture in road pavement.

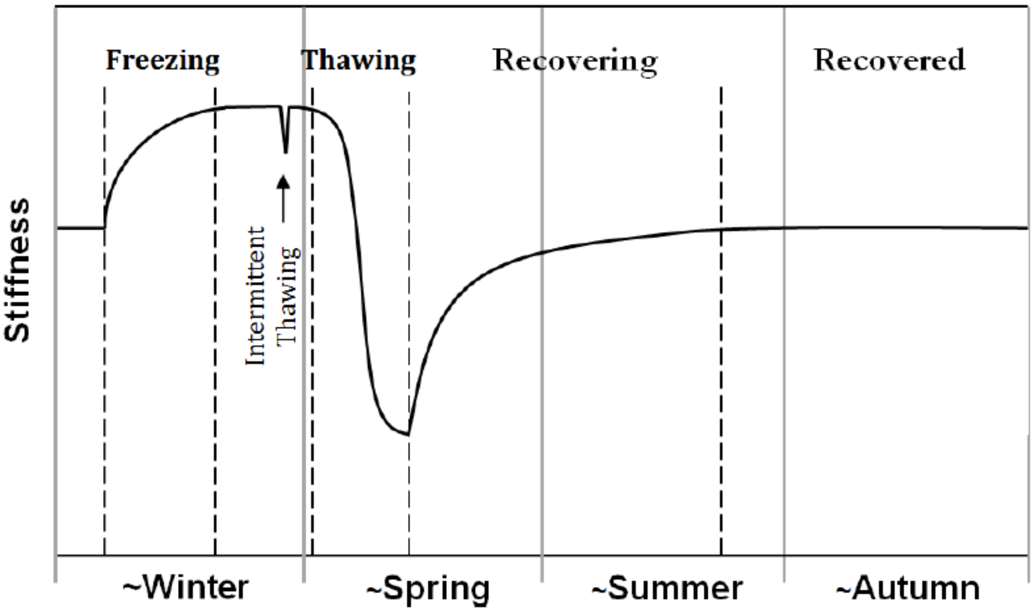


Figure 2-13 Conceptual Variation of Pavement Stiffness due to Freezing & Thawing (Salour, 2015)

Berthelot et al., (2008) conducted a study to monitor the seasonal changes in structural capacity in some thin-paved roads through FWD deflection tests. The outcome of the study reflects that the FWD deflection values can be used to evaluate the changes in structural capacity due to seasonal variations in moisture. Besides, there is evidence of increases in load carrying capacity of road pavements during the winter freezing and successive weakening of the pavement in spring thaw measured by FWD tests with various loads (Normal 40.0 KN up to 50% excess). The effect of uncontrolled moisture in road pavements is stated to be significant due to a combination of freeze-thaw cycles (Breakah et al., 2009). Ground-coupled thermistor data have been utilised for monitoring the variation of temperature in road pavements (Berthelot et al., 2008). Overall, there is scope for identifying the changes in structural capacity of road pavements due to changes in moisture and temperature in various seasons from FWD deflection tests.

Although moisture has a significant impact on pavement layer strength, very few attempts have been undertaken to correlate the deflection test data with moisture damage. In Roberts, Michel and Paine (2006), a pavement evaluation model, ‘STEP’ (Structural Testing and Evaluation of Pavements), is presented which is used by the road transport authority of New South Wales, Australia. Originally the STEP model was jointly developed by the

National Technical University of Athens and the Australian Road Research Board. This STEP model uses FWD test data for predicting pavement remaining life along with optimising the treatments based on the structural evaluation of pavements (Roberts et al., 2006). The NSW STEP appears to be promising because it introduces 'an explanatory model for linking unbound material strength to rainfall, subgrade characteristics, material properties, effectiveness of drainage and cracking of the surface. This model is calibrated from the analysis of six years' seasonal deflection data and has been successful in incorporating the effects of moisture while predicting pavement strength, remaining life, and rehabilitation treatment design (Roberts et al., 2006). To date, there has been no study conducted in New Zealand for evaluating the effects of moisture on road pavements based on deflection test, however, Patrick and Mclarin (1998) conducted a study for NZTA to provide future direction in research on moisture damage in road pavements. There was an indication that deflection (FWD) tests can be used for evaluation of changes in pavement strength due to changes in moisture. Based on the literature, it is obvious that a holistic approach is required for investigating the moisture damage in road pavements, therefore, the next section summarises the studies on the New Zealand road network.

2.6 Research on Moisture Damage Issues in New Zealand

The researches by Arampamoorthy and Patrick (2010), Hussain et al. (2011), Henning and Roux (2008), Henning et al. (2009) Werkmeister et al. (2006), Arnold et al. (2010), Parkman et al. (2003), Salt and Stevens (2001), Peploe (2002), Patrick and Mclarin (1998), Schlotjes et al. (2014) and Patrick et al. (2014), have been found relevant to this study. Although Austroads guides for pavement technology along with their New Zealand supplements provide general guidance about the effect of moisture on road pavements, there are requirements for identifying and addressing the moisture damage related failure especially in New Zealand. In addition, the development and use of Transit M/4 base-course specification has led the designers or engineers in the risk of assuming that pavement materials counter the effects of moisture in road pavements (Arampamoorthy & Patrick, 2010). NZTA is proactive in funding and conducting research on the effect of moisture in road pavements realising the importance on pavement performance. Patrick and Mclarin (1998) conduct a study for NZTA (formerly Transit New Zealand) for developing a guideline for further research on moisture in pavements. They have pointed out that similar studies were on-going under the SHRP programme (Heydinger, 2003) and Minnesota road research project (Ovik et al., 1999) in the USA. They suggested that further research on moisture in pavements can be implemented after reviewing the outcome of the research in the USA. Both studies were based on in-situ monitoring of temperature, moisture, frost, freeze-thaw cycle and long term evaluation of pavement stiffness with FWD deflection measurement. The outcome of the studies is promising in evaluating the seasonal fluctuations of pavement layer stiffness and developing the weighting factor for monthly changes in subgrade stiffness for use in design (Ovik et al., 1999; Heydinger, 2003). Although frost heave, freeze- thaw cycles and variation of temperature have been pointed out as affecting the changes in pavement layer stiffness, their effects on New Zealand roads are minimal. The long term monitoring of in-situ moisture and the deflection measurements with FWD as suggested for New Zealand road pavements by Patrick and McLarin (1998), can be considered suitable for this particular study.

In 2001-02, NZTA funded further research for evaluating the effect of changes in subgrade moisture due to seasonal rainfall and fluctuations of the ground water table (Peploe, 2002). Overall, the objectives of the research were to verify the applicability of soaked or unsoaked CBR strength of subgrade for the design of roads and also to investigate the seasonal influence on subgrade stiffness. Test pits were excavated at the left wheel track and the centreline of the track in three test roads in the Auckland region. Visual observation, in-situ CBR, DCP, and water content tests were done at each location. Three standpipes were installed in each road for locating the changes in ground water table during the monitoring period. In addition, laboratory soaked CBR tests were also conducted four times in a year for verifying the changes in subgrade stiffness. Overall the research output was encouraging for further research on moisture changes in road pavements. The soaked CBR test is suggested as appropriate if ground water table lies within 1 m of the subgrade during the year otherwise un-soaked CBR can be used for the design of roads. Little correlation was found between changes in ground water table and the amount of seasonal rainfall (Peploe, 2002).

Roberts et al. (2006) discussed the development of a model for predicting pavement remaining life and also for optimisation of structural treatment from FWD test data. This study also suggested calibration of the structural strength of a pavement with the changes in climate and drainage conditions. STEP and Pavement Life-Cycle Analysis Treatment Optimisation (PLATO) are the two models presented in Roberts et al. (2006). These models have been in use in Greece and New South Wales in Australia for pavement performance prediction and are based on long term FWD test data. Overall the models have successfully incorporated the real time prediction of pavement remaining life by the calibration of moisture and temperature changes along with the drainage parameters of road pavements (Roberts et al., 2006).

Patrick et al. (2014) conducted a study funded by the NZTA which was to investigate the importance of drainage in road network maintenance. They postulated that drainage improvement can be a cost-effective measure to reduce the extent of expenditure in pavement renewal. The study demonstrated the flow of water into the pavement layer. The finite element models also demonstrated how the surface and sub-surface drain can reduce the inflow of water into the pavement layer. In addition, a score-card based drainage rating system was presented that can be used to prioritise the drainage improvement (Patrick et al., 2014). However, the drainage rating system is a qualitative assessment of the road sections and the development and validity of the system is not comprehensively tested. Therefore, there is scope for further development of the drainage risk rating system based on a comprehensive risk analysis technique and sufficient validation.

2.7 Risk Principles in Road Asset Management

Risk is defined as the amalgamation of the possibility and consequence of an incident that might hamper the desired objective of a project or a task. It is estimated as a combination of the likelihood and the consequence of an event. The risk analysis technique is used to identify the level of risk based on the synthesis of available information for determining the likelihood and the consequences of any undesirable events (Transit New Zealand, 2004). The term ‘Risk’ refers to the likelihood of potential loss arising from any problems or complications in the system that may hamper the successful completion of the system (Rezakhani, 2012). In general, risk in construction projects refers to the complication, problems, and loss that may affect the achievement of desired outcomes. The popular notion of defining the risk is as follows.

Risk= Probability or Likelihood* Consequences of the Failure Equation 2-2

(Schlotjes et al., 2012)

Theoretically risk refers to uncertain, unexpected future events that may have serious implications. However, it is possible to manage the risks and take proactive actions in reducing its probability of occurring or its consequences (Choi, Cho & Seo, 2004; Khan & Haddara, 2012). The essential features of risk management are to identify, assess, prioritise, and implement proactive measures in reducing the likelihood or impact of any unexpected events (Rezakhani, 2012).

In construction and project management, risk analysis is applied to identify the uncertainty and the consequence of any undesired event (Chapman, 1997; Rezakhani, 2012). Road network management is a continuous programme and the road controlling authorities need to be aware of the on-going risks and take proactive actions to mitigate them. Road controlling authorities, including the New Zealand Transport Agency (NZTA) have an explicit risk management framework in place. The NZTA's risk management framework is included in Figure 2-14 below.

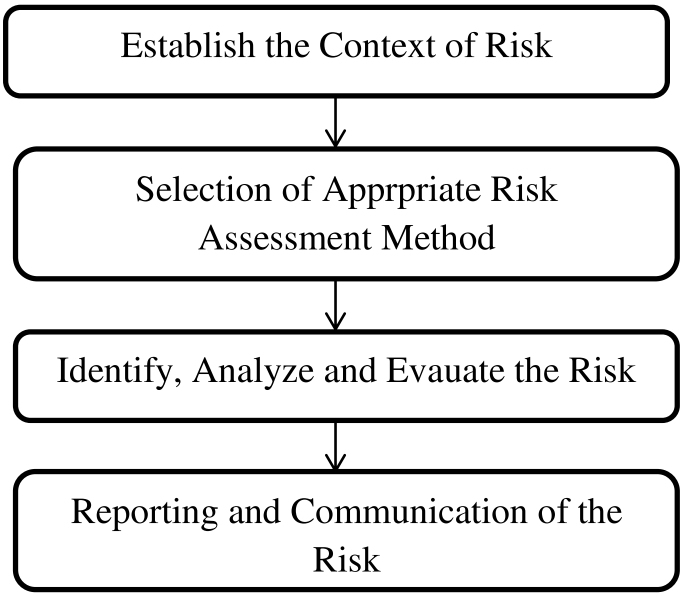


Figure 2-14 Key Elements of Risk Management Process (Transit New Zealand, 2004)

The four steps of the risk management framework developed and implemented by NZTA for road network management is comprehensive. The risk management framework includes the crucial stages of establishing the context of risk and identifying, analysing and evaluating the risks. Often, these tasks require extensive knowledge and expert judgment, especially to identify the hazards or factors and their associated risks. The risk management framework in Figure 2-14 is more suitable for project and traditional road maintenance contract management (Transit New Zealand, 2004).

Either quantitative or qualitative approaches can be used for risk assessment. The quantitative risk assessment is a complex process and requires a great deal of data for assessing the probabilities and consequences, and usually expresses the risks in numbers, or units of loss. Whereas, the qualitative risk assessment method is simple and deals with linguistic expressions of risk of the expert or the practitioners. The output of qualitative risk assessment may be simple indices or numbers or the linguistic expressions like low, moderate and high (Rezakhani, 2012; Khan & Haddara, 2003).

The important step in risk assessment is the utilisation of appropriate technique. In a broad sense these risk analysis techniques are either deterministic or probabilistic in nature. In other words, they are either classical or advanced mathematical model based risk analysis techniques. Some of the techniques used for risk assessment are summarised in Table 2-2.

Table 2-2 Brief Description of the Major Risk Analysis Techniques/ Models

Risk Analysis Techniques/Models	
Brief Description	**Applicability in the Research**
Fault Tree Analysis; Event Tree Analysis; Failure Modes Effects and Criticality Analysis and Support Vector Machine:	
These risk analysis techniques are close to each other in terms of their objectives and application method. The basic principles are to identify the undesired fault and event and their root causes. Then the relationship among the root causes of failure are critically analysed and represented by flowcharts (fault tree, event tree). Then both the qualitative and quantitative risk analysis, using the flowcharts, can be conducted to identify the likelihood of the occurrence of the top undesired event. These risk analysis techniques were developed based on their relevancy in manufacturing or process industries and electrical control system monitoring (Halme & Aikala, 2012; Patil, Waghmode, Chikali & Mulla, 2009; Schlotjes, Burrow, Evdorides & Henning, 2014).	This technique can be a good platform for qualitative risk assessment in road network asset management. However, the quantitative assessment (probabilistic analysis) may require a range of assumptions, especially to develop a framework to predict the risk of premature failure.
The support vector machine is a modelling tool that has been used to apply fault tree analysis in assessing the probability of failure in road pavements. The tool incorporates the generic fault trees developed for each of the major pavement failures (Rutting, Shear and Cracking) in road pavements (Schlotjes, et al., 2014).	The support vector machine is a platform that has been used as a binary classifier in identifying the probability of failure in road pavements. Its applicability in this research can be identified once the moisture damage factors have been identified.

Risk Analysis Techniques/Models	
Monte Carlo Simulation; Life Cycle Analysis; Sensitivity Analysis:	
The Monte Carlo Simulation is a computerised modelling technique that incorporates the simulation of a range of uncertainties (distributions) and produces a resultant distribution of possible outcomes. This distribution (likelihood) can generate the risk by considering the consequences of the uncertainties. The technique is based on graphical presentation and provides information about the likelihood and different outcomes due to the uncertainties involved. It requires a high speed software programme to perform the Monte Carlo Simulation and the uncertainties or root causes have to be presented by distributions (Normal, Log Normal, PERT etc.).The life cycle analysis involves the implementation of Monte Carlo simulation to determine the effect of life cycle cost of any asset against the different ranges of values of uncertainties (Schlotjes et al., 2014).	The risk assessment framework is planned to be a predictive framework. The range of factors (not uncertainties) responsible for occurrence of moisture damage (failure) in road pavements may not be practical to represent by any distribution.
The Sensitivity Analysis can be conducted using any of the above risk analysis platforms. In addition, the risk analysis technique involves the observation of changes in the top undesired event (likelihood) due to slight changes in the values of root causes (likelihood).	The sensitivity analysis can be a part of the desired risk analysis technique.
Stochastic Modelling; Bayesian Analysis:	
This modelling technique has been widely utilised in various sectors and is conceptually similar to the deterministic modelling techniques used in road asset management. The modelling involves the development of a matrix that essentially represents the current states of the assets. Then it is multiplied with a comprehensive transformation matrix to generate the resultant matrix which represents the states of the asset at a future date. The challenge is to develop the transformation matrix which is usually done by trial and error and using the back propagation technique. Similarly the high level Bayesian Analysis involves the transformation of a current probability (prior distribution) into the posterior distribution (Updated probability of uncertainty) based on the available data or information (Park, Smith, Freeman, & Spiegelman, 2008).	These forms of deterministic and probabilistic modelling techniques are widely utilised to identify the future maintenance need of a road network based on current pavement condition, level of performance and the budget constraints. The applicability of this high level machine technique in predicting drainage need (road sections at high risk of drainage) seems to be limited.

Risk Analysis Techniques/Models	
Artificial Neural Network Modelling: This modelling technique follows the basic concept of biological neural networks. Here a set of inputs (uncertainties) is connected via range of neurons (connectors) to the outputs. The connections between the inputs and outputs are trialled based on knowledge and experience. The connectors or neurons are assigned with adaptive weights during the training and these weights are adjusted through back-propagation methods. High level machine languages and programmes have made the ANN applicable in various sectors such as in robotics, traffic modelling, pattern and sequence recognition (Saltan & Terzi, 2008).	This high level machine (computerised) modelling has been used in transportation planning, traffic demand analysis, origin and destination analysis. The scope of this application can be further scrutinised once the moisture damage factors are identified.
Fuzzy Logic Model; Risk based Maintenance Technique: Fuzzy logic is a widely utilised tool for risk assessment. The model incorporates a number of inputs that are represented by membership functions. The model generates the output membership functions based on a number of inference rules based on expert judgement. The model is easy to develop and understand and can incorporate the linguistic expression of risks and generate rating through risk analysis (Rezakhani, 2012). This risk analysis technique was demonstrated in Khan and Haddara (2003). It is a comprehensive risk assessment method that involves scenario and consequence analysis, especially in manufacturing industries. The probabilistic risk analysis incorporates 'Monte Carlo Simulation' and the outcome of the analysis is transformed as the maintenance need.	The applicability of these risk analysis techniques is described further, especially to identify their suitability for the research.

Among the risk analysis techniques, Fault Tree Analysis (FTA), Fuzzy Logic model and Life Cycle Risk Analysis have been effectively used in project and construction management and natural risk assessment (Carr & Tah, 2001; Khan & Haddara, 2003; Reigle & Zaniewski, 2007; Zlateva, Pashova, Stoyanov & Velev, 2011). These risk analysis techniques are further elaborated to identify their reliability and applicability in the possible risk assessment framework.

2.7.1 Risk Analysis through FTA

FTA is a hierarchy based risk analysis model where a tree like chart is used to reflect the failure paths along with the causes and factors of the failures (NZTA, 2005). Here the failure path is identified through detailed study of the process, behaviour of the materials and a logical dependency between the causes and failure is developed through fault trees (Khan & Haddara, 2003). FTA is effectively utilised in process industries for developing the fault tree for an individual component or for the total plant where any single failure of a component may have a huge impact through shutting down of production. The developed fault tree can be used for risk assessment through Monte-Carlo or any other probability analysis tool (Khan & Haddara, 2003).

FTA as a diagnostic tool can be used for assessing the causes of any pavement failure. NZTA (2005) has recently conducted research on developing a diagnostic tool for assessing the failure probability of road pavements. FTA has been used for developing the failure paths for rutting, cracking and shear failure of road pavements. This method is preferred for the use of combination logic such as “AND”, “OR”, and helps to understand the interactions among the factors through multiple scenario analysis The developed fault tree for any pavement failure can lead to identify the mechanism of that failure. In addition, this failure path/tree can be used for probability based risk analysis for pavement failure. The Figure 2-15 shows a generic fault tree that can be modified or updated for developing failure paths for any road pavement (NZTA, 2005).

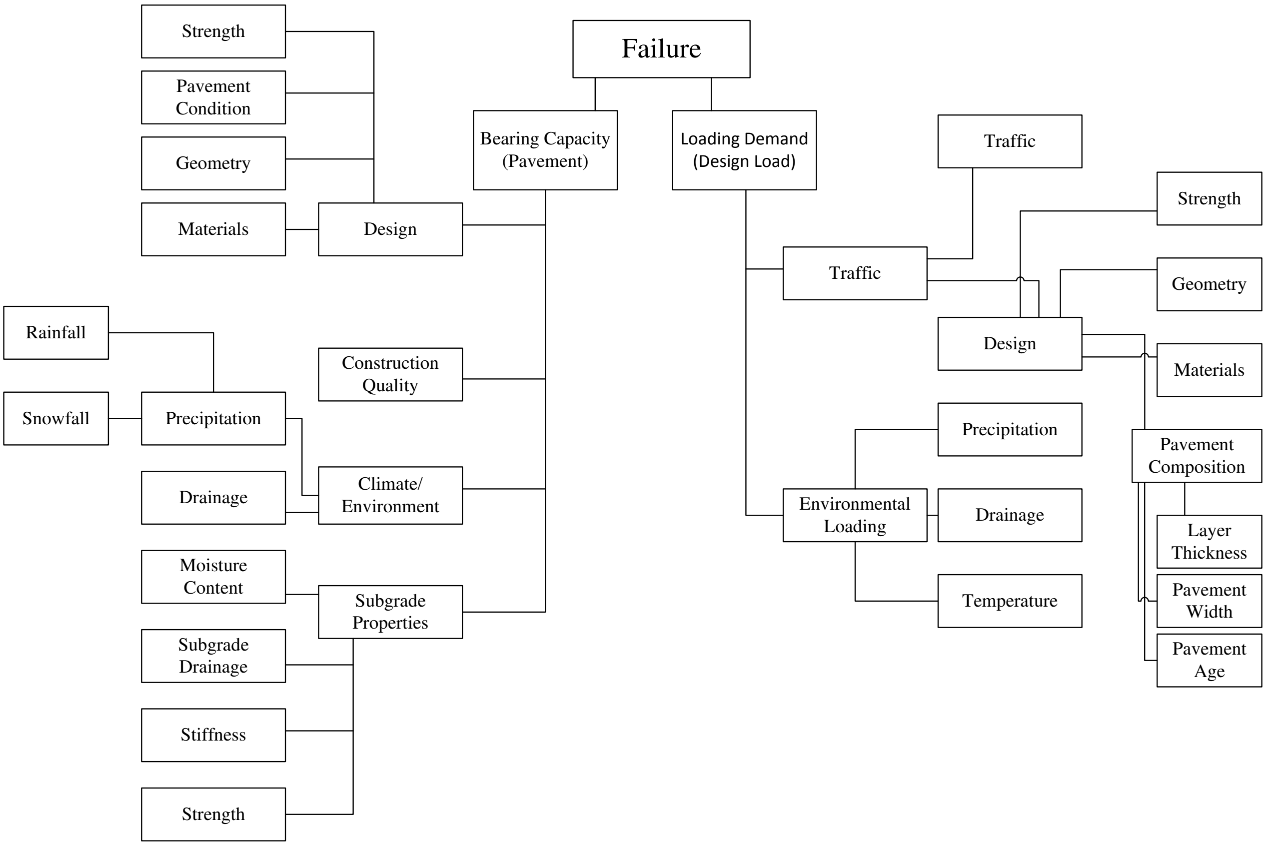


Figure 2-15 Generic Fault Tree for Road Pavements (Schlotjes et al., 2014)

2.7.2 Fuzzy Logic Model

The fuzzy logic model has been utilised for risk assessment in construction project (Carr & Tah, 2001). These fuzzy membership sets were first proposed by Lukasiewicz in the 1920s for representing a range of truth values using real numbers from 0 to 1. Later in 1960s, Zadeh developed the fuzzy logic model through amalgamation of possibility theory and fuzzy membership function (Carr & Tah, 2001). Fuzzy logic models can be used for defining linguistic variables using membership functions for further risk analysis. This helps in identifying the risk of any system through analysing expert’s comments or judgements. Figure 2-16 shows the membership functions for defining subjective inputs of the fuzzy logic model for risk assessment.

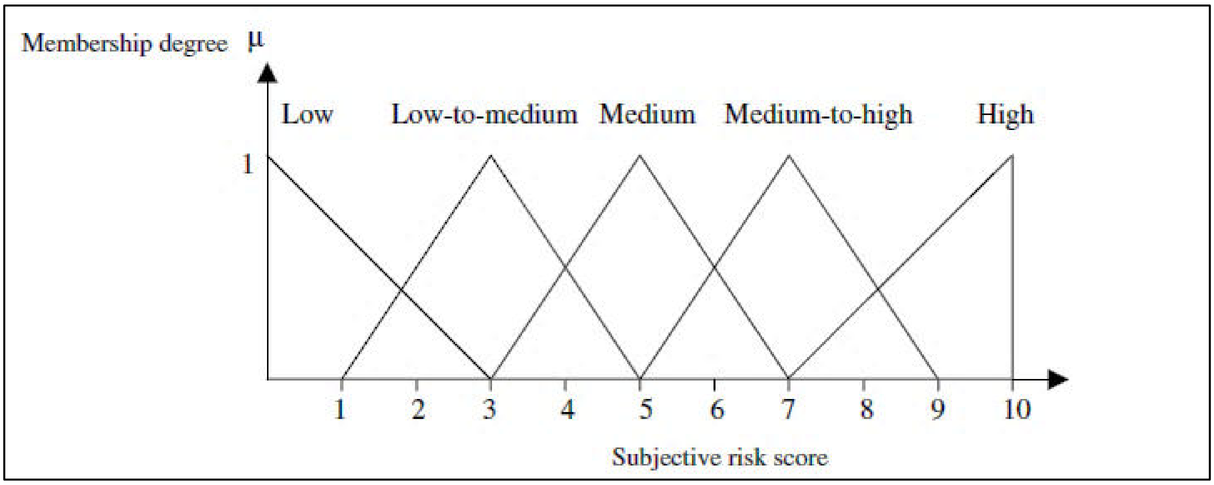


Figure 2-16 Membership Function for Inputs (Dikmen, Birgonul & Han, 2007)

The fuzzy logic model is usually designed as a multilevel hierarchical system that generates a risk assessment output after analysing the pre-defined inputs or factors through 'IF-Then' based inference rules (Zlateva et al., 2011). Figure 2-17 shows an example of a multilevel hierarchical fuzzy logic model where two risk factors form a sub-system which has an output. This sub-system output interacts with the third input and forms the second sub-system. Thus the fuzzy logic system is developed as a multilevel hierarchical system and generates a complex risk assessment output.

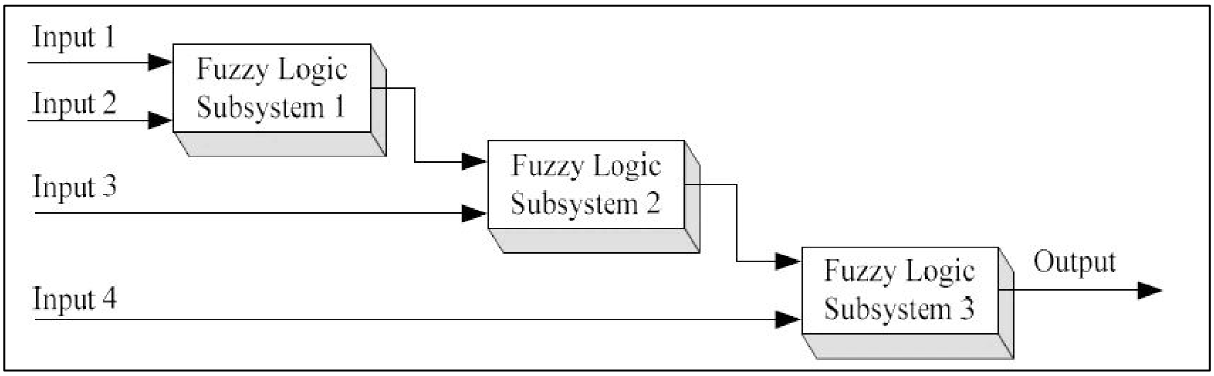


Figure 2-17 Structure of a Multilevel Fuzzy Logic Hierarchical Model

The objective of the fuzzy logic model in risk analysis is to develop a relationship between the risk factors, risks and their consequences through cause and effect diagrams. These cause and effect diagrams or the membership functions can be applied to identify the relationship between the risk sources and their consequences (Carr and Tah, 2001). Dikmen et al. (2007) developed a fuzzy risk assessment methodology for identifying the impact of cost overrun on international construction projects. Influence diagrams have been used for estimating the cost overrun risk rating for an international company and the reliability of the risk assessment method has been tested using company and project information. The diagram in Figure 2-18 is the membership function denoting the cumulative construction risk rating.

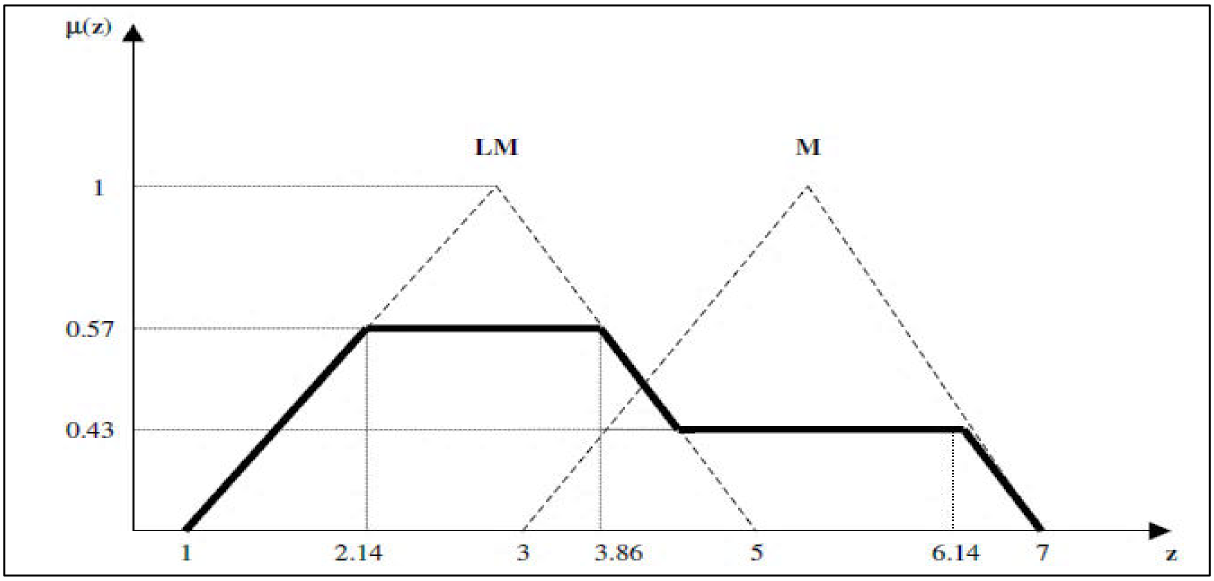


Figure 2-18 Membership Function for Construction Risk Rating (Dikmen et al., 2007)

Cho, Choi and Kim (2002) adopted a fuzzy membership curve for defining uncertainties in the construction project risk assessment. They designed the methodology for incorporating uncertainties using the fuzzy logic model involving both the probabilistic parameters and subjective judgement. The diagrams in Figure 2-19 were developed for representing the uncertainty range for ground settlement and injury/fatality in construction projects (Cho et al., 2002).

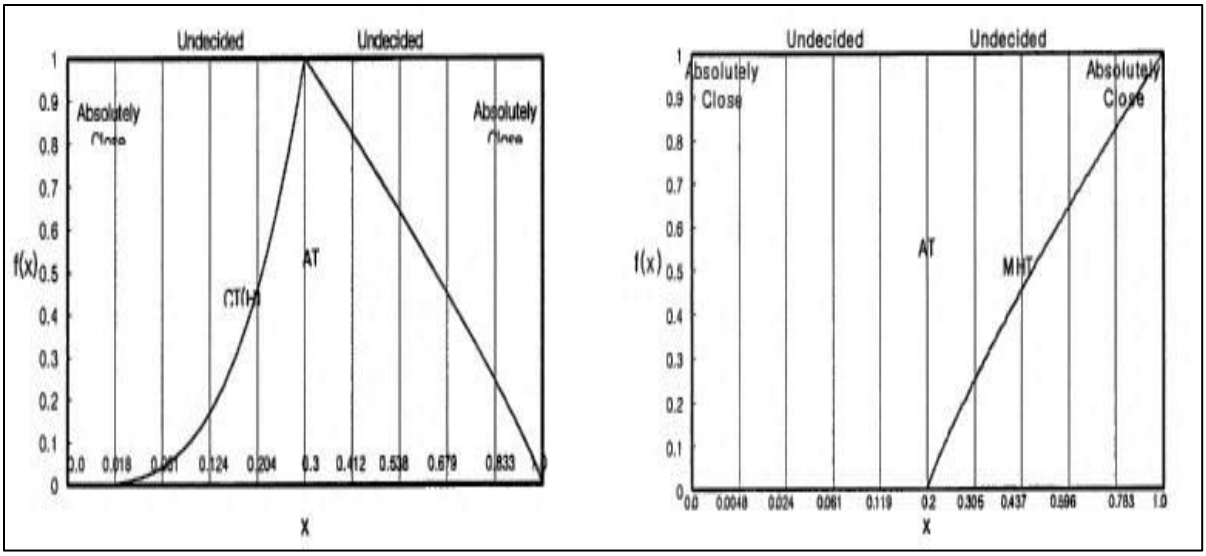


Figure 2-19 Membership Curve for Uncertainty Range for Ground Settlement and Injury/Fatality (Cho et al., 2002)

2.7.3 Life Cycle Based Risk Analysis

Life cycle based risk analysis is another approach for risk assessment that can be implemented in construction project or pavement management (Reigle & Zaniewski, 2007; Walls & Smith, 1998). This form of risk analysis has integrated the concept of life cycle cost analysis of any system for identifying the relation between the risk and its sources or factors. Life cycle cost analysis is a decision making tool that road controlling authorities adopted for selecting the optimum pavement rehabilitation or maintenance strategy (Reigle & Zaniewski, 2007).

The diagram in 2-20 shows theoretical life cycle cost (maintenance) curve of a road section. The horizontal axis is the effective life of the road pavement and the vertical axis is the cost of maintenance. There is a large spending at the beginning of the life cycle of a road pavement. Usually this is the construction cost of the new pavement or the rehabilitation cost. Then there is minor maintenance cost for a while at the life cycle. After that, there is another increase in maintenance cost of resurfacing or refurbishing of the pavement. The next phase is to maintain the road till there is a sharp increase in maintenance cost to ensure the level of service. This stage in the life cycle indicates that the pavement reached its end of life cycle and the next feasible option is to replace or rehabilitate the road pavement.

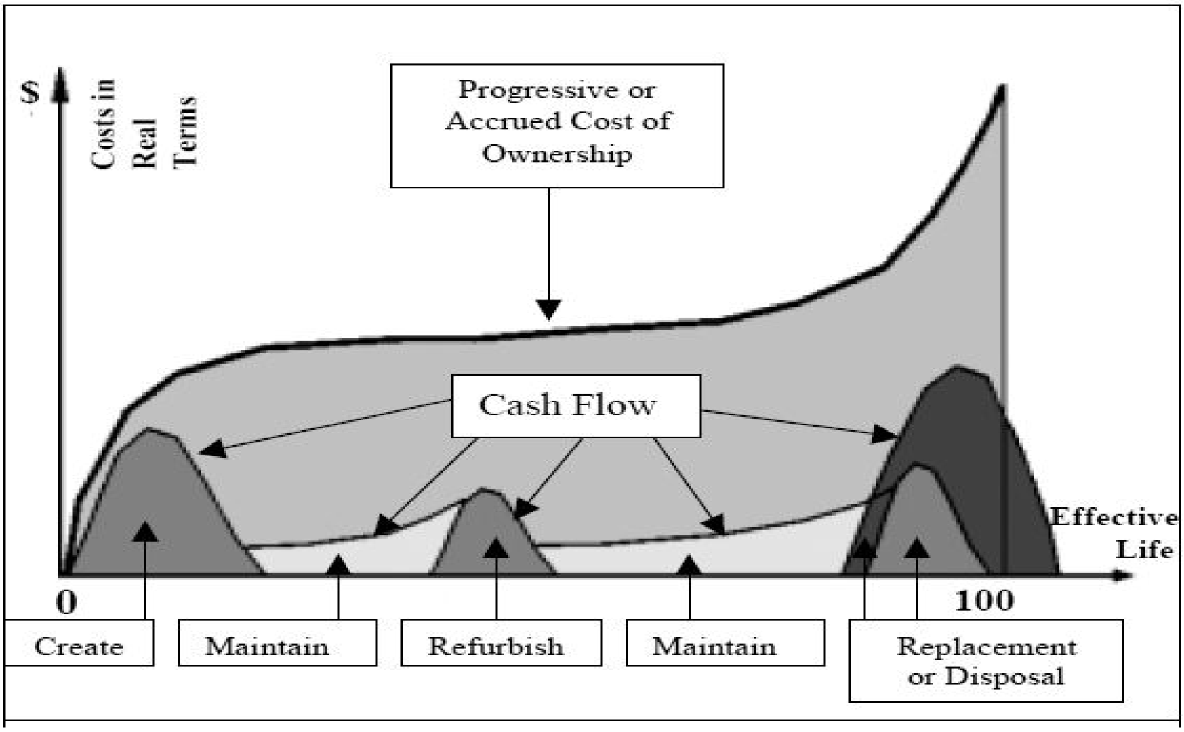


Figure 2-20 Conceptual Life Cycle Cost Model for Road Pavement Maintenance (NZTA, 2014)

Life cycle cost analysis of road pavements involves the identification of the agency cost and the user cost, both discounted to a single net present worth value. Here agency costs referred to the costs incurred by the road controlling authorities and include the initial construction cost, routine maintenance, rehab and any preventive maintenance cost. Whereas the user costs referred to as the accident cost, user delay and excess vehicle operating costs and usually incurred by the road user. The Equations 2-3 and 2-4 have been used to identify the net present worth of any particular preservation strategy for discounting annual agency and user costs over an analysis period of N years.

$$\textbf{NPV= Initial Cost+ } \sum_{k=1}^{N} (Agency\ cost + User\ cost)^{k}\ \textbf{(PWF)} \qquad \textbf{Equation 2-3}$$

$$\textbf{Here PWF (Present worth factor) = } \frac{1}{(1+i)^{n}} \qquad \textbf{Equation 2-4}$$

And i = discount rate, n= years of expenditure

The structure of the life cycle based risk analysis consists of a number of inputs or parameters that optimises the best design, maintenance or rehab treatments. Inherent uncertainties involved in those parameters are considered in the risk analysis model. Reigle and Zaniewski (2007) had developed a risk-based life cycle cost analysis model for project level pavement management. This model generates probability distributions of the present worth cost, the agency worth cost and the user worth cost for various preservation strategies. In addition, a sensitivity analysis was conducted for identifying the impact of each input parameter on the model output. The Life cycle cost analysis model, Monte-Carlo simulation is the most favoured simulation technique for detecting the probability distribution of any preservation strategy. Figure 2-21 gives an example of a probability distribution derived from risk analysis through life cycle cost analysis model. The model output represents the probability of the preservation treatment that may be required over the analysis period. This probability distribution helps the user in developing a maintenance strategy to increase the life cycle of the road pavement.

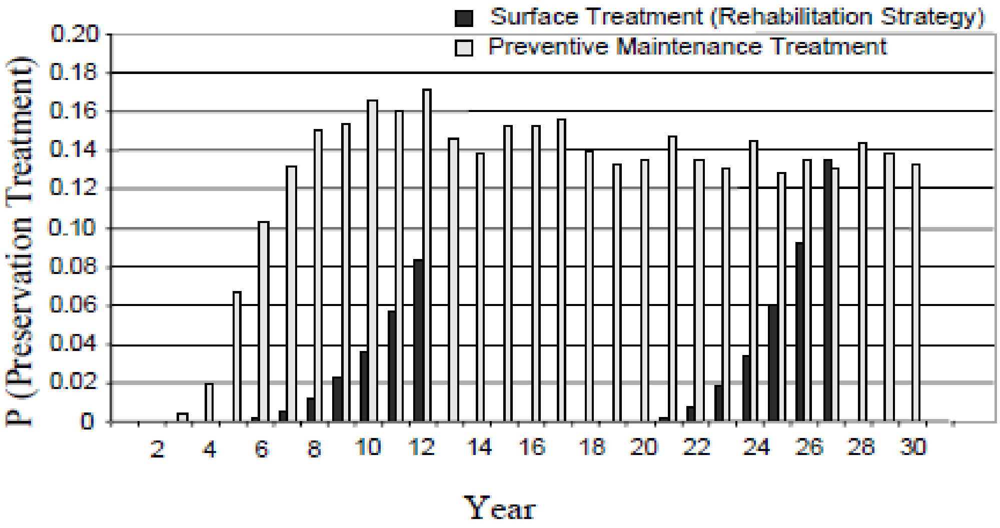


Figure 2-21 Probability Distribution for Preservative Treatment of Road Pavements (Reigle & Zaniewski, 2007)

2.8 Summary

The literature review covered a range of topics on moisture damage potential in flexible road pavements. The mechanisms of moisture damage in both types of flexible pavement were discussed in this chapter. The review includes a number of studies on the moisture susceptibility of asphalt pavements and on various test methods to identify the susceptibility. However, the structural asphalt pavement is mostly used on motorways and urban road networks. Then the mechanism of moisture damage in the granular flexible pavements was investigated. The effect of moisture on flexible pavements and the resultant distress mechanisms was scrutinised further to develop a knowledge basis. A number of studies, including laboratory, field test and accelerated loading tests were found to reflect the effect of moisture on flexible granular pavements in New Zealand (Arampamoorthy & Patrick, 2010; Arnold et al., 2010; Hussain et al., 2011). Some other studies were concentrated on modelling of major distress mechanisms (rutting, cracking, flushing) in road pavements in New Zealand (Henning et al. 2009; Kodippily, Henning, Ingham & Holleran, 2014).

This research is focused towards the development of a framework that can be used commercially, especially in road network management. In this regard, the research conducted by Schlotjes et al. (2014) to develop a diagnostic approach for major pavement distresses and by Patrick et al. (2014) to develop a framework to optimise the drainage maintenance and its effect on road pavements in New Zealand, provided some guidelines in developing the methodology for this research. The research is expected to develop a framework or methodology that can be implemented to identify and prioritise the road sections for drainage improvement. This is particularly important in terms of road network maintenance in New Zealand.

The road controlling authorities in New Zealand, especially the NZTA, have focused more on increasing the investment in sectors like drainage improvement. This has been considered as a proactive measure to increase the life cycle of road pavements. Although the NZTA has provided some basic guidelines for planning and prioritising the drainage improvement works in their road network (NZTA, 2014). Their expectation is that industry should come forward and develop their own prioritisation methods, especially to ensure efficient investment in drainage improvement. Although there were a couple of studies conducted in this respect, still there is scope to improve the understanding of the effect of moisture on road pavements, to identify the factors that may induce moisture damage and essentially to generate the drainage need of any road network.

To date, the studies were focused on understanding the effect of water or moisture in road pavements, and the methodology to identify the pavement distresses caused by excess water (Arampamoorthy & Patrick, 2010). Therefore, this study has focused more to develop a predictive framework that can identify the factors responsible for moisture damage in flexible road pavements. The predictive framework can be conceptualised as a rating based risk assessment methodology that can identify the drainage deficiency of a road network. The scoring based criteria prescribed by Patrick et al. (2014) to identify the drainage need of a road network is a simplistic way of addressing the issues. This study can thereby focus on developing the predictive framework that essentially involves a comprehensive risk analysis technique.

The literature review provided a background study on the major risk analysis models. A brief description of major classical and advanced risk analysis models has helped to assess their applicability in the framework. Some of the risk analysis models were discussed in detail. These risk analysis techniques were chosen based on the characteristics of the predictive framework and the nature of the moisture damage factors that will be the basis of the framework. These comparative studies were helpful in identifying the candidate risk analysis techniques for the research. A contribution of the research is to identify the risk assessment framework that can be introduced in drainage need analysis. Although the concept of risk assessment is utilised in road network management, its application for addressing the moisture damage potential can be considered as an area with further potential for improvement.

The review also incorporated studies that reflected on the development of a new approach or framework and provided guidelines on the research methodology (Cho et al., 2002; Gidel et al., 2001; Schlotjes et al., 2014). These studies demonstrated the case study based application and evaluation of their frameworks. This research can incorporate a comprehensive case study based evaluation methodology for the proposed risk assessment framework. As the framework is expected to be utilised in the commercial sector, the framework needs to be disseminated among practitioners. In New Zealand, the collaborative approach among road controlling authorities and the network management entities is a classic example of stewardship in the road asset management sector. This has helped in identifying the most efficient approach to road network management in New Zealand (NZTA, 2014a). Overall, the case-study-based evaluation method can be an example of developing a predictive framework and evaluating it based on the actual performance in predicting the risk of the road sections. The literature review has provided specific guidelines for accomplishing the major objectives of the research. The next step is to develop the detailed methodology of the research in order to accomplish the desired objectives of the research.

Chapter 3: Methodology

3.1 Introduction

Based on a review of the available literature and the knowledge gained from field visits, a ‘Moisture Damage Risk Assessment’ (MDRA) framework can be formulated for predicting the potential for moisture damage and associated risks of failure in flexible road pavements. The MDRA framework comprises of two modules the ‘Risk Identification’ and the ‘Risk Analysis’. The risk analysis module includes the fuzzy logic model, FTA and the ‘Combination of the Moisture Damage Factors’ as the candidate risk analysis techniques. These risk analysis techniques have been applied for moisture damage risk assessment of road sections (case studies in next three chapters) in order to evaluate their performance and applicability in risk assessment. A comparative study for evaluating the three risk analysis techniques has been undertaken and their advantages and disadvantages have been considered for selecting the suitable technique for the final MDRA. The MDRA has been developed and validated based on the data from a road network in New Zealand. The framework of the proposed MDRA is presented in Figure 3-1.

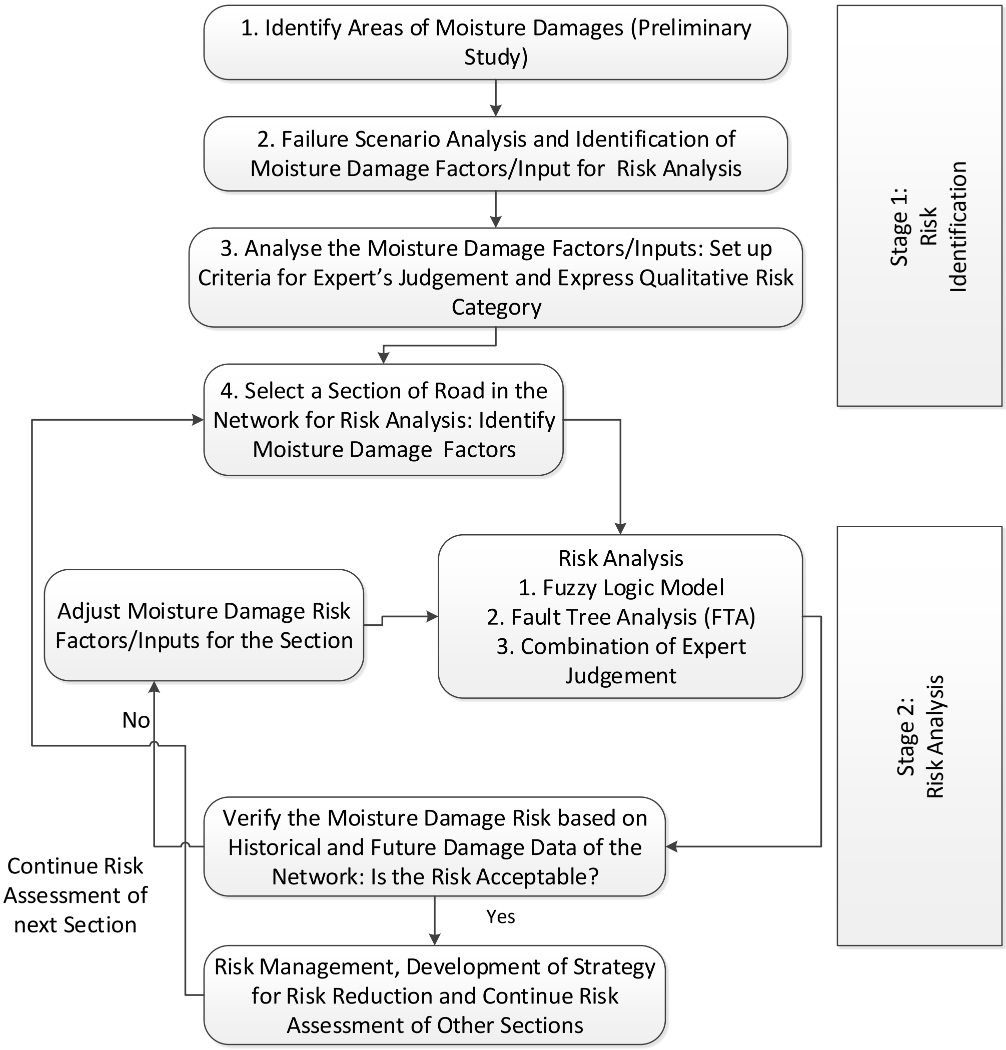


Figure 3-1 Framework of the MDRA

The physical inspections and high speed survey data (here in Figure 3-1) of the road network have been adopted for identifying the risk scenario and the factors or inputs for risk analysis. The survey includes the high speed video recording of the road network. After that, a preliminary study will identify the moisture damage factors or inputs for risk analysis. Then a set of criteria based on the review of the literature and expert judgment will be established for describing the moisture damage factors along with linguistic expressions of risk. Once the factors are identified, the next step is to conduct a detailed assessment of each road section. The risk analysis will be conducted through the three different candidate techniques (Figure 3-1). A comparative study will help to identify the most suitable risk analysis technique which can be recommended for use in the MDRA. The output of the risk assessment can be used for developing the drainage risk profile of the network.

3.2 Description of the Road Network (Data Source)

New Zealand is a long (approximately 1500 km in north-south direction) and narrow (400 km in east-west direction) country of about 268,000 sq. km. Due to the geophysical characteristics of the country, the road network stretches from north to south and possesses the highest length of road per person in the world. The total length of the road network is 93,000 km; among them 11,000 km are major State Highways which are of sealed pavements. Among the State Highways only 199 km of motorways are built as asphalt pavement. The rest of the State Highways are composed of granular chip seal road (NZTA, 2013a, 2014).

The road network (West Waikato South), shown in Figure 3-2, used for this study is in the north-west region of New Zealand. The majority of the road network is composed of low volume rural highways. The Average Annual Daily Traffic (AADT) of the road network ranges approximately from 500 to 10,000. The road pavements are predominantly chip seal with bounded (cement) granular base course. One tenth of the road network consists of stone mastic asphalt surface with granular base course. The weather and rainfall do not vary significantly across the sub-network. The region has warm, humid summers and mild winters with west and south-west winds. The rainfall across the sub-network varies from 800 to 1600 mm/year and the average is 1250 mm/year. Only a small portion of the road network is exposed to moderate to high rainfall areas (Waikato Regional Council, 2014). Weather and rainfall parameters may not vary significantly among the subdivided road sections of a site; however it may vary for road sections of different State Highways. The geography and wet areas vary among the 100 m road sections of a site. The geography of the road network varies from flat-rolling ground in rugged hilly areas. Large portions of the road pavements in the network are constructed of cut and fill. In addition, many major streams, including tributaries of the country’s longest river run across the road network. Therefore, the geophysical variations of the road network have notable effects on the proposed risk assessment framework.

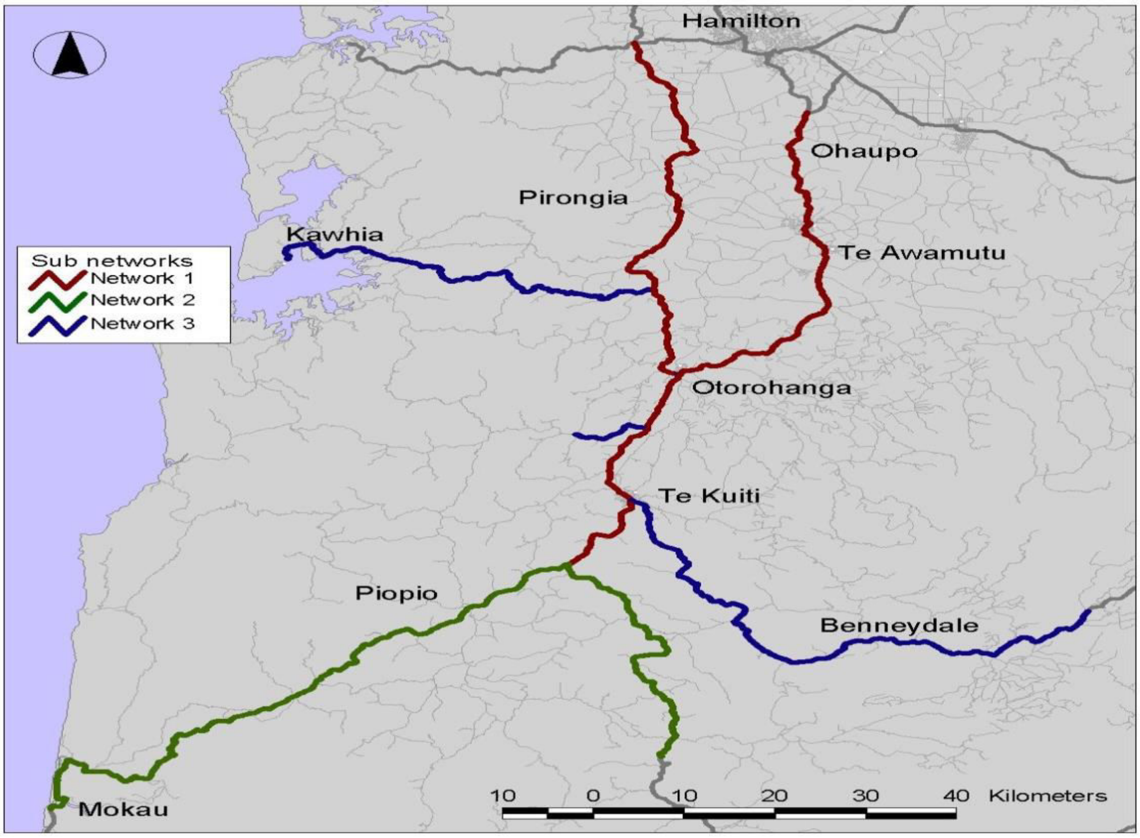


Figure 3-2 West Waikato South Road Network (Transfield Services Ltd, 2014)

Figure 3-2 and Table 3-1 gives the location and distribution of the West Waikato South road network in New Zealand. The road network is divided into three sub-networks based on their classification and level of service. The network has been managed as a performance based contract since 1999, and, as part of the contract, it has been evaluated regularly against the network performance measures.

Table 3-1 Distribution of State Highways in Road Network

Sub-network	State Highway Class	Rural (Km)	Urban (Km)	Total (Km)
1	Regional Strategic	125.73	20.61	146.34
2	Regional Connector	56.80	4.23	61.03
3	Regional Distributor	136.31	2.36	138.6
Total		318.84	27.20	346.04

3.3 Risk Identification

Risk identification is designed to assess the risk events for any project based on the information acquired during the assessment (Cho et al., 2002). A road section is part of a system that has a number of components, and the objective of the system is to ensure the mobility of the traffic. Risks in the context of pavement management systems evolve from the likelihood or probability of failure of any component of the road section. The consequences of the failure include the disruption to the traffic flow and an increase in maintenance cost (Khan & Haddara, 2003; Choi et al., 2004). The first step of the risk identification is to collect moisture damage related information for identifying the risks in the network. The road network chosen for this study is in the northeast part of the country and the geomorphology of the area varies from flat terrain to steep hills, and includes large streams and rivers. The subgrade strength also varies significantly over the network due to the presence of volcanic pumice soil (Daly, 2004).

3.3.1 Preliminary Study

A preliminary study was conducted in August to October, 2013. The network was divided into road sections of 100 m in length. The 100 m road sections are considered effective because the FWD tests are usually done at 50 m intervals in alternate lanes. Sixty road sections from five rehabilitation sites were selected for the preliminary study. These road sections had been surveyed through video recordings in May and July 2013, and undertaken physical inspections in September 2013. Pavement layer properties and strength data were collected from the road asset management database and FWD test data. The video survey data were used for detecting the presence of geophysical and surface factors that may induce moisture damage in road pavements. Some sub-surface factors are responsible for moisture damage in road pavements as well. These factors were collected from the road asset management database. The composition and structural strength of the road pavement were acquired from the road asset management database and the FWD and sub-surface investigation (trenching or coring) test data of the network, respectively. Overall the preliminary study helps to identify the possible factors and suggests further investigation during the detailed study, which helped in developing a list of moisture damage factors for the MDRA.

The moisture damage factors will be evaluated based on their severity and documented for network analysis. The next challenge will be to set up the criteria for quantifying those moisture damage factors through linguistic variables. The first set of criteria for risk analysis will be formulated using knowledge gained from the literature review and the expert knowledge of the managers of the road network. This network has been managed by the same organisation since 1999 and they have developed an intensive knowledge on the network. Their knowledge and expertise will be helpful in developing the initial criteria for risk analysis. However, these criteria will be adjusted based on the evaluation of the risk assessment method in predicting moisture damage or failure. This will be achieved through the validation of the risk assessment method.

3.4 Risk Analysis Techniques

It is proposed to conduct the risk analysis using the most suitable analytical method from either a fuzzy logic model (Dikmen et al., 2007; Carr & Tah, 2001; Cho et al., 2002; Zlateva et al., 2011), combination of moisture damage factor and FTA (Schlotjes et al., 2014) to develop the failure path and risks of failure in road pavements. These risk analysis techniques were found suitable through the assessment of the available techniques in literature in section 2.6. All three risk analysis techniques will be trialled and a case study based comparative study will be conducted to evaluate the techniques. This will be helpful in achieving the most efficient and effective risk analysis technique for incorporating into the MDRA. The three risk analysis techniques are detailed in the following sections.

3.4.1 Fuzzy Logic Model

The fuzzy logic model is a hierarchical risk analysis technique with several inputs, with the output representing the moisture damage risk of a road section. The inputs to the risk analysis correspond to the moisture damage factors expressed in linguistic variables. The linguistic input variables (moisture damage factors) will be represented by the five membership functions: “Low”, “Low to Medium”, “Medium”, “Medium to High”, and “High”. The moisture damage factors will be assessed in the interval [0 to 10] using the membership functions similar to that shown in Figure 3-3.

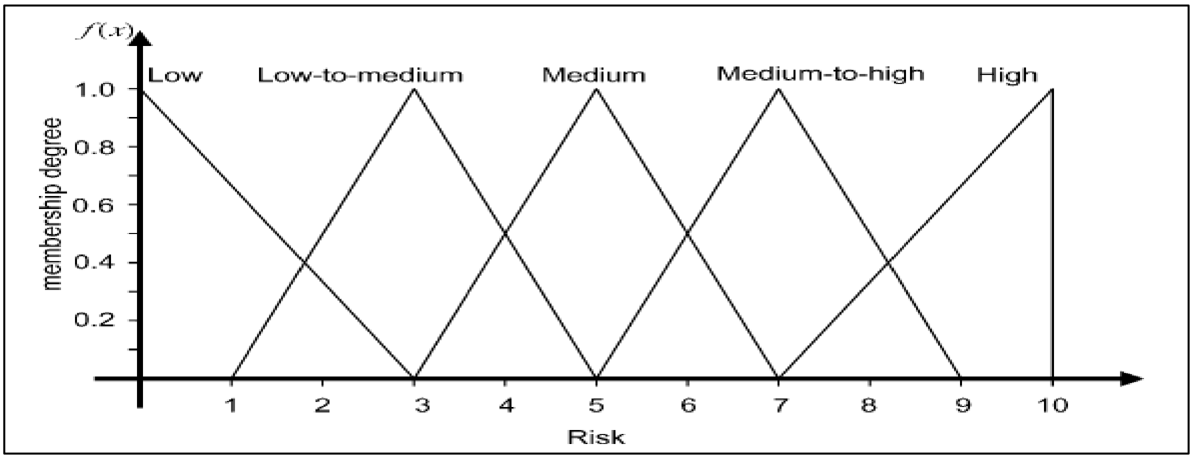


Figure 3-3 Membership Functions for Expressing the Moisture Damage Factors (Carr &Tah, 2001)

These linguistic variables will reflect the severity of the moisture damage factors and their relative impact on risk assessment. The number of inputs and the level of the hierarchy of the fuzzy risk assessment model will depend on the number of moisture damage factors obtained from the preliminary study. Two inputs or moisture damage factors will develop a fuzzy logic subsystem and its output will be an intermediate variable. This intermediate variable will interact with another input and will develop the second fuzzy logic subsystem. Thus the risk analysis process will continue based on a number of "If-Then" logic based inference rules. The inference rules will be formulated based on expert judgment and can be adjusted during the validation of the risk assessment method. The output of the risk assessment will be expressed by fuzzy membership functions, "Very Low", "Low", "Medium", " High", and "Very High" in the interval [0 to 100] (Zlateva et al., 2011) similar to that shown in Figure 3-4.

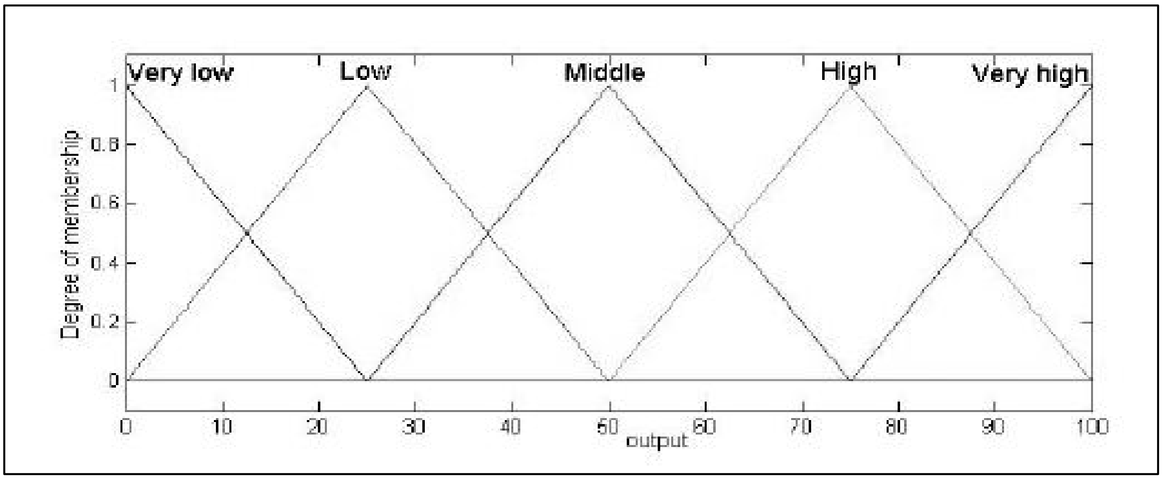


Figure 3-4 Membership Functions for Presenting the Output of the Risk Analysis (Zlateva et al., 2011)

In addition, there is scope to develop a set of membership curves representing the degree of uncertainty of any risk event. The membership curves can be used for determining the uncertainties of risk events like weak subgrade, uncontrolled vegetation, and poor surface drainage.

3.4.2 Fault Tree Analysis (FTA)

A fault tree can be effectively used in pavement management for presenting the causes and the critical path of any failure (Schlotjes et al., 2012). FTA is used for probabilistic failure analysis through determining the frequency of occurrence of any damage. FTA has been successfully applied in developing rutting, cracking and shear failure paths in road pavements. FTA will be used to develop the Moisture Damage Fault Tree (MDFT) showing the failure paths due to moisture damage potential in road pavements. The development of the MDFT will involve the following steps. The knowledge gained through the literature will help in identifying the predominant types of moisture damage in New Zealand road pavements. Expert knowledge will be incorporated for improving the knowledge base;

- **Identification of the failure factors:** This will be achieved through a literature review and incorporation of expert knowledge during a field trial for identification of moisture damage factors. Moisture damage factors identified through the risk identification stage will be used as the failure factors for developing the MDFT; and,
- **Identification of the relationship among the factors and the failures:** Statistical relationships in the form of correlation and distribution will be used for identifying the key relationships in developing the fault trees. Data will be used from the road network in New Zealand to develop the FTA based risk analysis technique.

The developed fault trees will be used in this research for identifying the probability and risk of moisture damage failure. A set of data from the network will be used for training, and case studies had been conducted to verify the applicability of FTA in risk assessment.

3.4.3 Combination of the Moisture Damage Factors

This risk analysis technique was conceptualised in the course of the research. This technique combines the risk ratings of the moisture damage factors determined through subjective judgements of experts. In road asset management, subjective judgement plays an important role, especially in pavement condition rating and prioritisation of pavement preservation maintenance (NZTA, 2014). Here, the risk assessment model incorporates expert judgement while rating the moisture damage factors based on a number of parameters.

The Figure 3-5 shows the basic steps incorporated in analysing the moisture damage risk of any road section or site.

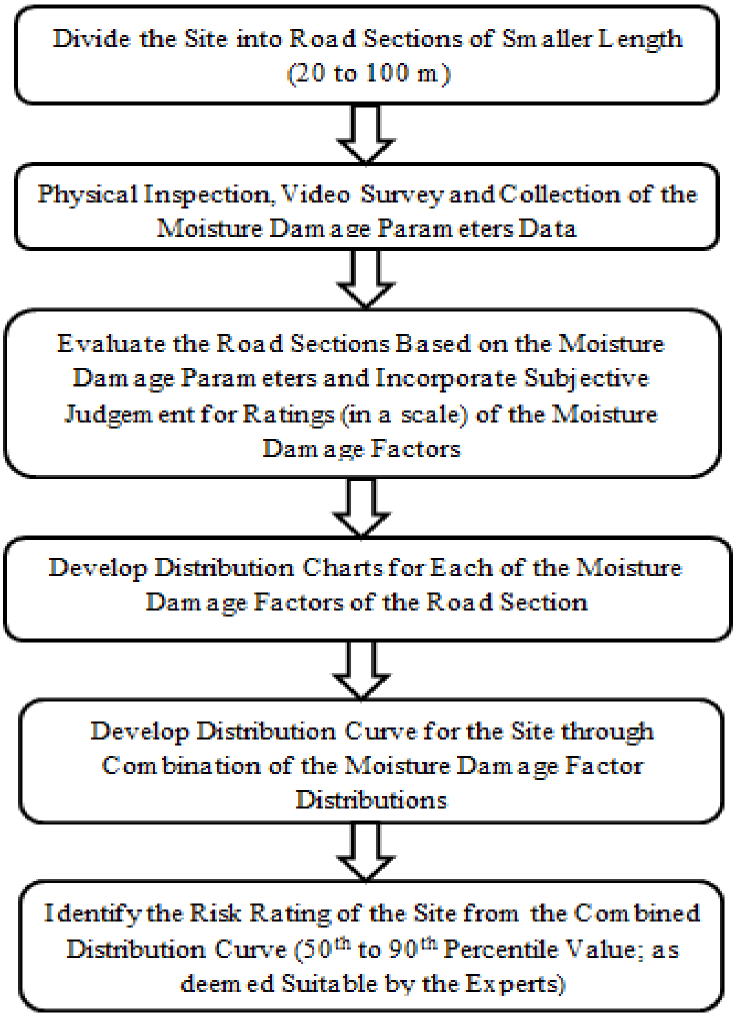


Figure 3-5 Risk Analysis through Combination of Moisture Damage Factors

This risk analysis technique is conceptualised based on the principle of superposition. The distribution curves for each moisture damage factor has been developed using the values of the smaller road sections of the site. Then, the distribution curves (moisture damage factors) for the site will be superimposed or combined to generate the resultant curve that essentially represents the moisture damage risk of the site. The risk rating of the site can be obtained based on any central tendency (50th to 90th percentile) value as deemed suitable by the practitioners.

Figure 3-6 shows an example of the combination of two distribution curves. Here the ‘Model Risk’ add-in for Microsoft Excel is used to combine two distributions. In Figure 3-6, two distributions (A, B) are combined and the resultant curve (bottom) eventually represents the weighted aggregate of the two curves. Thus the distribution curves of the moisture damage factors can be combined to generate the resultant curve that may yield the risk rating of the road section.

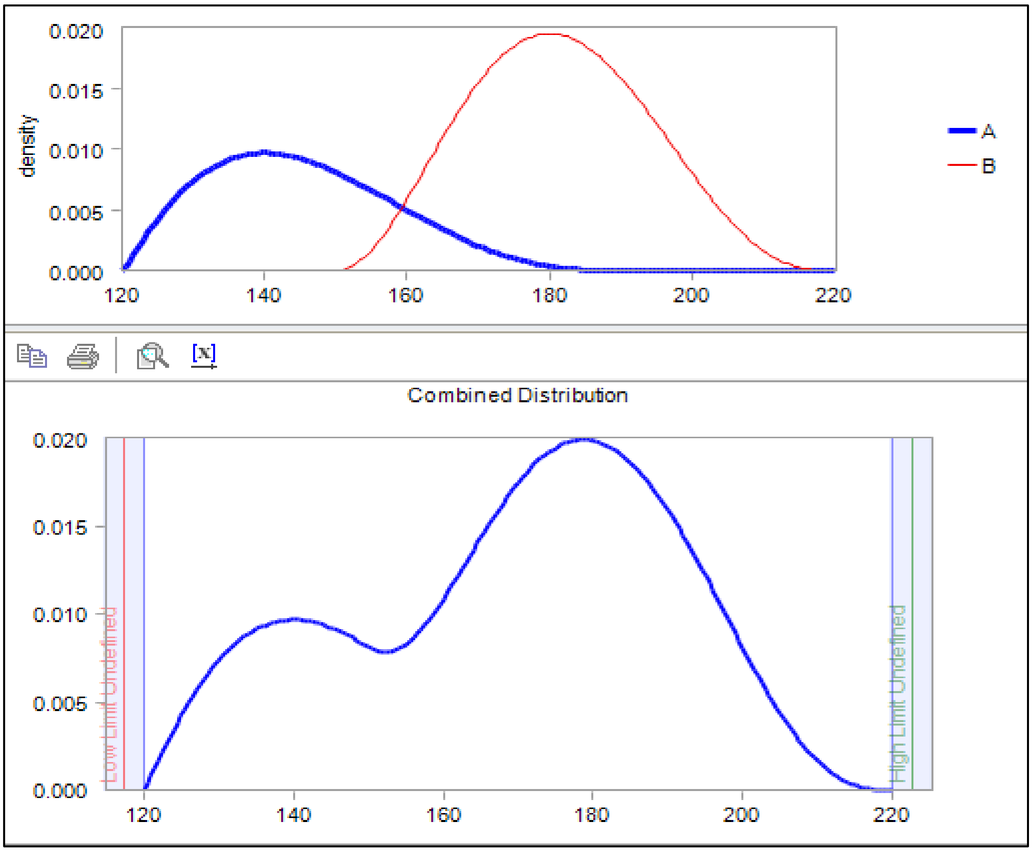


Figure 3-6 Combination of Two Distribution (Model Risk)

3.4.4 Comparison of the Risk Analysis Techniques

The three candidate risk analysis techniques will be trialled in the MDRA. They will be used for evaluating the moisture damage risk of road sections in the network. The road sections of the network were observed for the next two years and their performances in the wet and dry season were monitored. In addition, the historical data available from the road network were used for identifying the trends of failure of the road sections. Then a comparative study for identifying the premature failure and performance indicators like roughness, rutting, and cracking will be conducted. This will help in comparing the actual performance of any road section with the predicted risks identified through MDRA. The following methods have been formulated for evaluating the three risk analysis techniques adopted in the research.

- Evaluate the performance of each risk analysis technique using appropriate performance measures. Performance measures may include the speed, reliability, repeatability and adaptability of the techniques and performance of the technique in handling the research dataset.

- Finally, the risk analysis techniques will be evaluated on the basis of their performance in predicting the moisture damage risks in road pavements.

3.5 Evaluation of the MDRA for Reliability and Effectiveness

The third objective of the research is to validate the proposed MDRA. This will be achieved through monitoring of the road sections in two consecutive wet and one dry season. Figure 3-7 indicates how the validation process will be undertaken.

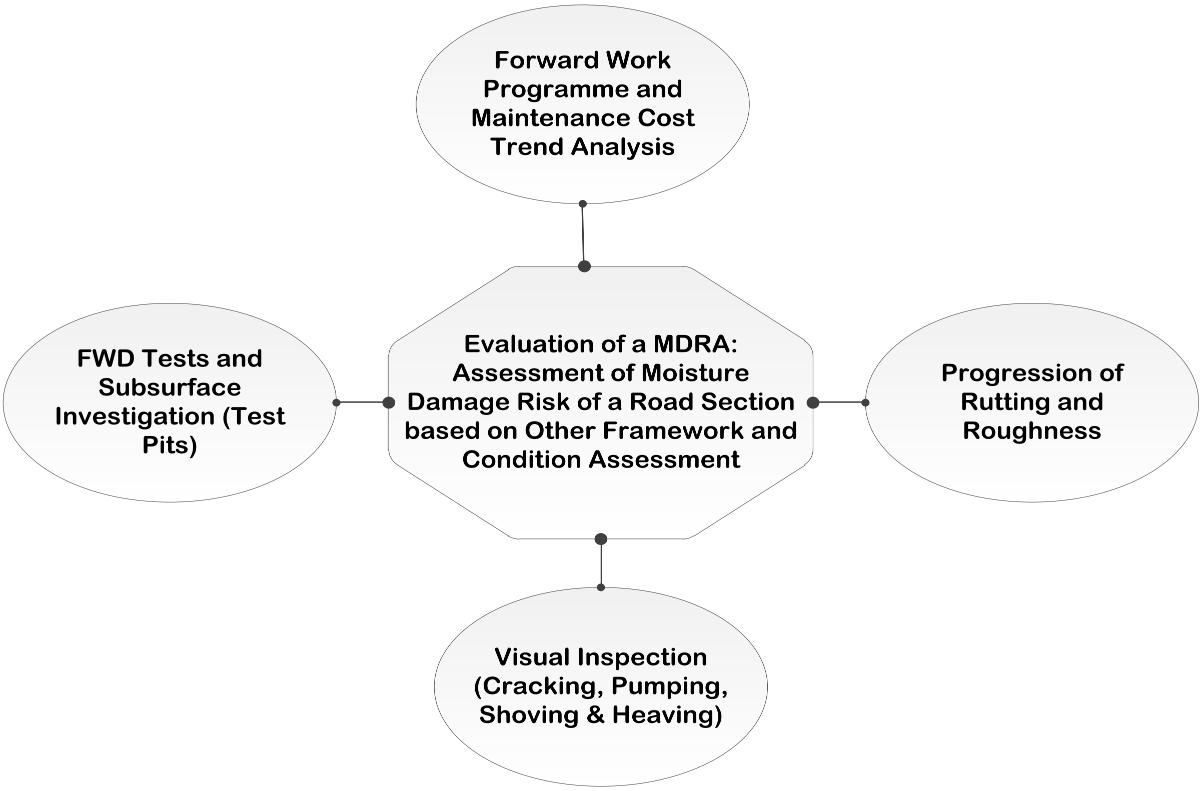


Figure 3-7 Evaluation of the Reliability and Effectiveness of MDRA

Every year rehabilitation works are conducted for network improvement and for maintaining the level of service. The level of the routine maintenance work has a positive effect on the road network performance especially on the improvement of the Pavement Serviceability Index (PSI) value of the road network (Fwa and Sinha, 1986). Therefore, monitoring sites will be selected from the road network based on the risk classification of MDRA. Data will be collected from a number of representative sites of each risk class. These monitoring sites will preferably be selected from the rehabilitated sites completed from 2009-10 to 2012-2013. The FWD and other test data are available for these rehabilitation sites. The pavement damage data on those sites would give an indication about the premature failure in road pavements. Each of the sites will be monitored from July 2013 to July 2015 for moisture damage based on the tests or indicators in Table 3-2.

Table 3-2 Tests/Indicators for Validating the MDRA

Test/ Indicator	Measurements/Subjects	Frequency and Reason for the Test
FWD Deflection Test	Deflections for monitoring the strength of subgrade and pavement layers	FWD tests will be carried out during wet and dry spells over the year. The normalised central deflection, radius of curvature, lower layer index, and base layer index (Horak, 2008) derived from the FWD data will give an indication about the subgrade and pavement layer's strength. Multivariate analysis of these test data will be useful in evaluating the effect of moisture on the subgrade.
Progression of roughness	The extent of damage from potholes and other irregularities due to moisture in road pavements.	Road roughness are regularly monitored and measured over the network. Road roughness in NAASRA/IRI will be collected from those sites. Moisture related damages like ruts, cracks and potholes on road pavements induce an increase in roughness value. The signs of sudden increase in road roughness, compared to the average roughness over the road section, might be used for indicating the risk of moisture damages. So the changes in roughness value over the wet and dry seasons will give an indication about the changes in level of service and associated risks from moisture damage.
Progression of rutting	Accelerated rutting will give an indication of permanent deformation of subgrade due to traffic loading and the presence of moisture. However, it is difficult to differentiate between rutting due to traffic and moisture, so the level of increase in rutting among the road sections of similar traffic will be considered.	Rutting will be measured over the seasons for monitoring the deformation of the subgrade. It will be measured over the year for trend analysis against the risk assessment. It is expected that the rate of rutting increase in high risk areas will be more than low risk areas. The objective is to verify whether the acquired rutting data corroborate with the assessed risk through MDRA. In order to accomplish this objective, the increase in rutting will be used as a parameter for evaluation of the MDRA.
Visual inspection of Cracking	Road surfaces at the selected sites will be observed for cracking. This will be done either through visual or video recording inspection.	Cracking in the road surface will be monitored during the wet and dry spells of the year. Cracks in the road pavement allow water to enter into the pavement so the extent of cracking should be monitored for verifying the risk of moisture damage. The estimated

Test/ Indicator	Measurements/Subjects	Frequency and Reason for the Test
		percentage of cracked areas will be used as an indicator of moisture damage in road pavements.
Subsurface investigation (Coring)	Cores will be collected and tested in the laboratory from the severely damaged areas or areas showing signs of pumping or shoving. Visual inspections and unconfined compressive strength of the cores will be conducted for evaluating the moisture damage.	The cores will be collected for evaluating the reduction of strength due to moisture in granular pavement layers. Some moisture damage factors like high water table in cut areas, old or distressed surfaces, topography of the road, pavement shoulder can be evaluated from the sub-surface investigation of road pavements through coring and laboratory testing.

FWD test data collected over the network during rehabilitation works have been used for analysis. Additional visual inspections for cracking and rut depth measurement will be carried out during the research. The cores for sub-surface investigation will be collected by the contractor and will be tested in the laboratory. The above tests conducted on the selected sites should indicate the extent of moisture damage in road pavements. The extent of moisture damage observed during the monitoring period should corroborate with the risk prediction based on MDRA. It is proposed to use multivariate analysis for verifying the corroboration of the test data and predicted risk of road sections in the network.

3.6 Summary

The adopted methodology of the research is presented in this chapter. It indicates that there is scope to develop a framework for network level assessment of moisture damage potential in flexible road pavements. In this regard, MDRA a new risk assessment framework has been proposed as the basis of the framework. The long term application of the MDRA in road network management is promising in various aspects. This form of risk assessment can assist in identifying the drainage needs of a road network. The assessment of risks of moisture damage is particularly important for the New Zealand road network because moisture is considered as one of the critical deteriorating factors for major flexible road pavements.

Chapter 4: Development and Application of the Fuzzy Logic Model

4.1 Introduction

This chapter describes the development and application of one of the candidate risk analysis models in the research. The reason for selecting the fuzzy logic model as a risk analysis technique in the MDRA was presented in the previous literature review and methodology chapters. However, the chapter begins with a brief background of the application of the fuzzy logic model in road asset management. Then the methodology of the development and application of the model is presented. In the results and discussion section, the outcome of the preliminary study, identification of the moisture damage factors, and the development of the different parts of the model are presented. Finally, a case study reflecting the application of the model in drainage needs assessment is included in this chapter.

This chapter demonstrates the development and implementation of a risk analysis technique as part of the conceptual risk assessment methodology for identification of the moisture damage potential in flexible road pavements. The model presented in this study is one of the candidate risk analysis techniques of the MDRA framework that is presented in Chapter 3 and Mia et al., (2014). The MDRA is expected to assist asset managers in identifying the areas at high risk of moisture damage coupled with insufficient drainage measures.

The study was conducted in a road network in New Zealand consisting of mainly low to moderate volume rural highways. These roads are predominantly constructed as granular pavements with a thin chip seal surfacing. The climate and precipitation do not vary significantly over the region and can therefore be assumed uniform for the purpose of the study. The climate and precipitation information about the region can be obtained from Waikato Regional Council (2014). However, the topography of the region varies significantly, and has therefore been considered as one of the factors contributing to moisture damage in the road pavement. Although the risk analysis technique has been designed for the road network used in this study, it can be adapted for use on any network with requisite modification and verification.

4.2 Application of Fuzzy Logic Model in Risk Assessment

Fuzzy logic theories were first proposed by Lukasiewicz in the 1920s and were further developed by Zadeh in the 1960s. He developed fuzzy logic, based on the application of possibility theory into the mathematical logic system. Zadeh (1978) introduced the fuzzy sets to define the concept of a possibility distribution as a fuzzy restriction which acts as an elastic constraint on the values that can be assigned to a variable. The fuzzy logic model is incorporated to formally define the vague linguistic terms such as "low risk", "close to" or "good" condition, through membership functions and utilise them for risk or opportunity analysis (Carr & Tah, 2001; Zadeh, 1978). The risk analysis technique is used to determine the likelihood, and consequence of the risks on projects or tasks within the project. In particular, the fuzzy logic model can be implemented within the process of determining the magnitude levels of the risks that affect the desired objectives of a project (Carr & Tah 2001; Dikmen et al., 2007). Table 4-1 below summarises the studies from the literature where the fuzzy logic model has been adopted for risk analysis in different sectors.

Table 4-1 Application of Fuzzy Logic Model in Risk Analysis

Areas and Scope of the Research	Study
The fuzzy logic model was used as a hierarchical approach to identify the environmental risk of the south-west region of Bulgaria. Landslides, mud-rock flows, floods and seismic hazards have been used as the inputs and the output is the complex natural risk. In the model, the inputs are categorised as low, middle and high and presented in the interval (1, 10) by a trapezoidal membership function. The output is presented by a triangular membership function of the interval (1,100) and described linguistically as very low, low, medium, high and very high. The model includes "If-Then" based Mamadani inference rules in the Matlab fuzzy logic toolbox and the developed natural risk assessment system appears to be simple and effective as well as efficiently incorporated the knowledge and experience of experts in risk assessment.	Zlateva et al., (2011)
This study evaluated the application of the 'fuzzy Analytical Hierarchy Process (AHP)' and the 'fuzzy technique for order preference by ideal situation' for prioritisation of pavement maintenance and repair works. The pavement condition (distress) data were collected through condition surveys and subjective rating of the experts. Pavement maintenance objectives such as road safety, pavement surface preservation, road operational status, and road aesthetics were identified from case studies. Thin hot mix asphalt overlays, resurfacing, slurry seals, cape seal, micro surfacing and fog seal were the treatments for pavement maintenance. Both	Ouma, Opudo and Nyambenya, (2015)

Areas and Scope of the Research	Study
of the techniques were found to yield the similar prioritisation ranking however, fuzzy AHP was slightly overestimating the ranks of the prioritisation.	
A channel-safety assessment of a commercial port was conducted based on a fuzzy logic model. Hydrometeorology, channel condition, traffic factor, and management level were considered as the major risk factors of the channel. The channel safety is the basic output of the risk assessment and is presented linguistically as secure, basic security, more insecure, unsafe and very unsafe. A triangular membership function in the scale of 1 to 10 has been used for fuzzy risk analysis. Overall the fuzzy logic model was described as more effective and user focused compared to the traditional probability based risk assessment system.	Wu and Hu (2014)
A pavement condition assessment method was developed based on expert judgment using the fuzzy logic model and the AHP. Roughness, deflection, surface deterioration, rutting and skid resistance were used as the performance indicators for pavement condition assessment and prioritization. The fuzzy membership functions (trapezoidal) with respect to the linguistic evaluation set (very good, good, fair, poor and very poor) were developed through a survey of experienced engineers. The process involved with open discussion, negotiations, and trade-offs and, finally, development of a comparison matrix of relative weighting of the performance indicators. Any road segment can be evaluated through the pavement condition assessment and can be expressed both linguistically and numerically using the ‘maximum grade principle’ and “defuzzified” cumulative index.	Sun and Gu (2011)
A Fuzzy Inference System (FIS) was utilised to estimate the pavement condition based on the pavement distress data. Traditionally this was done through comparison of the pavement distress data against the threshold values. The rankings of ‘cracking’, ‘bleeding’, ‘patching’ and ‘ravelling’ were used as the input for fuzzy analysis. Inference rules were developed based on the knowledge from the case studies. The FIS rule based system was used to develop a fuzzified Pavement Condition Index (PCI) for classification of the road section for prioritisation. The result of the study indicated a good agreement between the fuzzy logic based classification and the traditional PCI based classification of the road section.	Mahmood, Rahman, Nolle, and Mathavan, (2013)
A risk assessment methodology for underground construction was developed. The fuzzy membership model presented in the study incorporated a risk analysis based on probabilistic parameters and subjective judgments. Parameters such as pile driving, improper excavation, road restoration and concrete work were considered as the prime reasons for construction damage. Unexpected change in design, defective construction, loss of equipment and materials, injury, fatality, natural calamities and project delay were presented as the major risk scenarios that may cause substantial financial risk.	Choi et al., (2004)
This study developed a fuzzy logic based computational methods for pavement condition rating (subjective) and maintenance need assessment of a road network. The inputs of the fuzzy logic model were single or multiple cracks, alligator cracks, shoving, rutting, corrugation, pothole, ravelling, and bleeding. The road section were ranked as ‘Low’, ‘Medium’,	Fwa and Shanmugam, (1998)

Areas and Scope of the Research	Study
and 'High' based on the severity criteria. The low ranked roads were recorded for further monitoring whereas, the high category road section were prioritised for mandatory repair and maintenance.	

The scope of the fuzzy logic model in risk assessment is wide and focused towards the utilisation of knowledge and expertise of the stakeholders. To date, it has been widely utilised in environmental, construction, project, and channel safety risk assessment as discussed in Table 4-1. However, a few studies utilises the application of fuzzy logic models in road asset management, introduced the development of pavement condition assessment, and classification based on expert judgment (Sun & Gu, 2011; Ouma, Opudo & Nyambenya, 2015; Mahmood, Rahman, Nolle, & Mathavan, 2013; Fwa & Shanmugam, 1998).

4.3 Methodology

The methodology of the application of the fuzzy logic model in the moisture damage risk assessment is part of the overall implementation of MDRA which has been explained in Chapter 3. The sites were selected for the case study from among the rehabilitation sites from 2010/11 to 2012/13. These sites were selected because of the availability of the data, and represent the overall topography, traffic, and climate of the region. The risk analysis technique has been developed and implemented in three stages, as presented in Figure 4-1 and discussed below.

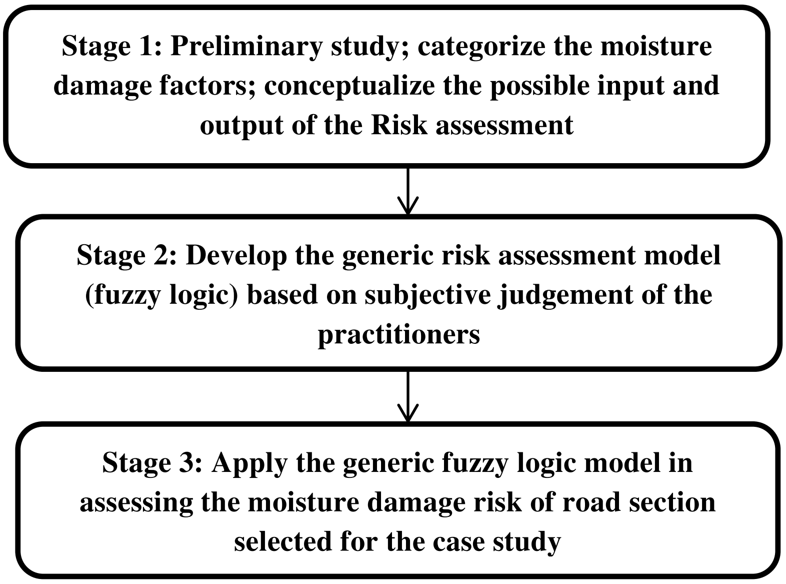


Figure 4-1 Development Stages of the Risk Analysis Technique

Stage 1:

A comprehensive literature review and field investigations were conducted to identify the possible factors of moisture damage in flexible road pavements. In the course of doing that, a risk assessment based framework (MDRA) was conceptualised to identify the drainage need of the road network.

Stage 2:

In this stage a generic fuzzy logic based risk analysis model was developed using the MATLAB program. The methodology to develop the model is presented in Figure 4-1. The basic steps followed to develop the risk analysis technique were;

1. Define the inputs and output of the moisture damage risk analysis technique;
2. Define the membership functions for the inputs and the output;
3. Develop the inference rules based on engineering judgment; and
4. Analyse and simulate the output of the risk analysis.

The risk analysis technique was developed in the MATLAB programme, using the Mamadani logic based inference rules (Zlateva et al., 2011; Wu and Hu, 2014). The development of the risk analysis technique is further elaborated in section 4.4 where the generic model is presented. The generic risk analysis model was developed through incorporation of the engineering judgment of the experts. The case studies were conducted in a road network in New Zealand. A technical workshop was conducted with the experts of the organization and their technical partners. The participants of the workshop were persuaded to give feedback on the generic risk analysis model, especially on the inputs (factors), output and the inference rules of the model. Another objective of the workshop was to present the risk analysis model to the sponsoring organisation. Initially the generic model developed by the researchers was presented. There was a question-answer session where participants provided their feedback. Later on they were divided into groups to discuss the different features of the model. The groups were requested to present their suggestions on the generic model. Overall the workshop was deemed successful and the feedback received was helpful in finalising the risk analysis model.

Stage 3:

The final step of this study was to apply the fuzzy logic based generic model. The road sections of the 10 sites were analysed through the risk analysis model. These sites were divided into equal road sections of 100 m length. Each road section was considered as a single unit for the purpose of the risk analysis. The road sections were investigated through physical inspection and video recordings collected in July 2013 and April 2014. The video recording was conducted by the inspection vehicle equipped with a video camera. Figure 4-2 shows the screenshot of a video file of a road section. The video files are easy to analyse because they can be scrutinised at various speeds and angles. These video recording files are regularly used in road network inspections for network performance assessment.

Road: 003-0088 from 15657.00 to 27.93
Survey Date: <survey_date>
Image: chainage: 15656.00 speed: 15.95 frate: 3.42 heading: 0.00 gps: 0.00000000, 0.00000000

Figure 4-2 Screenshot of Rover Video of a Road Section

4.4 Results and Discussion

The outcome of the study has been presented in two different parts. Part 1 presents the development of the generic risk analysis technique. It was developed using the fuzzy inference system in the Matlab programme. In part 2, the generic risk analysis technique is applied to identify the moisture damage risk of 100 road sections in ten different rehabilitation sites.

4.4.1 Fuzzy Logic Based Risk Analysis Model

The generic risk analysis model has been developed based on the knowledge gained from the literature review and the detailed field investigation conducted on the road network (Mia, Henning, Costello & Foster, 2013). The key challenges of developing the generic model were:

- To identify the moisture damage factors and categorise them as inputs for risk analysis;
- To set up the inference rules based on engineering judgement, literature review and expert knowledge; and
- To run the risk analysis and report the output of the risk analysis model.

4.4.2 Moisture Damage Risk Factors (Input)

Usually pavement distresses like rutting, roughness, flushing, potholes, shoving and heaving are considered as signs of pavement failure (Austroads, 2008b). However, these distress mechanisms can be consequences of excessive moisture in the pavement formation. The objective was to look for factors that may be the causes or sources of excess moisture in road pavements. A comprehensive literature review helped to identify the factors that may be responsible for excess moisture in the pavement formation. The factors responsible for pavement failure identified in some of the studies are presented in Table 4-2.

Table 4-2 Summary of Studies to Identify Moisture Damage Factors

Description	Study
A diagnostic approach to identify the causes of rutting, cracking and shear failure was presented. Excess moisture in the pavement formation was considered as one of the reasons for premature failure due to rutting and shear (Austroads, 2008b). Water ingress, inadequate surface and sub-surface drainage, thin pavement layer, inadequate horizontal gradient, unsealed shoulder, high ground water table, and excessive fines in the aggregate, old pavement, excess plasticity, sharp curves, materials quality, and construction quality were all considered as the causes of the predominant failures in road pavements.	Schlotjes et al., (2014)
This research result presented a scoring system to identify the drainage risk of a road section. Factors like climate (rainfall and freeze), topography, and position of drainage, pavement type, traffic level, water ingress, and drainage condition were identified as the factors responsible for drainage risk. These factors were scored as low to high (1 to 3) and the total score indicates the relative drainage risk of a road section. The total score ranges from 6 to 24 and an increase in total score indicates the relative increase of the drainage risk of a road section.	Patrick et al., (2014)

In addition, case study based preliminary studies were conducted on road sections (100 m length) from 5 different sites in the network. The objective of the case studies was to identify the factors that may be the cause of excess moisture in the pavement formation. The case studies helped to identify the factors that can be used for moisture damage risk analysis. The outcomes of the preliminary study indicate that a number of factors may be responsible for the presence of excess moisture in the pavement formation. The case study data were used for identification of factors (presented in Table 4-3 and Figure 4-4) that may be responsible for increasing moisture damage risk of the road section.

Table 4-3 Geophysical and Other Factors Scrutinised in the Preliminary Study

Site	Sections (No)	Flat/Rolling (%)	Upward (%)	Downward (%)	Sag Curve (%)	Hor. Curve (%)	High Stress (%)	Side Hill (%)	Side Bush (%)	Side Stream (%)	Culvert/Pipe (%)	Moisture Damaged (MD) Sections
A	10	30	20	60	30	70	80	100	70	90	50	30
B	13	8	69	15	8	62	69	69	69	46	54	85
C	9	44	22	33	33	67	89	44	78	89	44	100
D	15	53	20	20	20	40	40	13	93	20	20	27
E	13	8	15	77	8	77	77	85	85	23	15	85

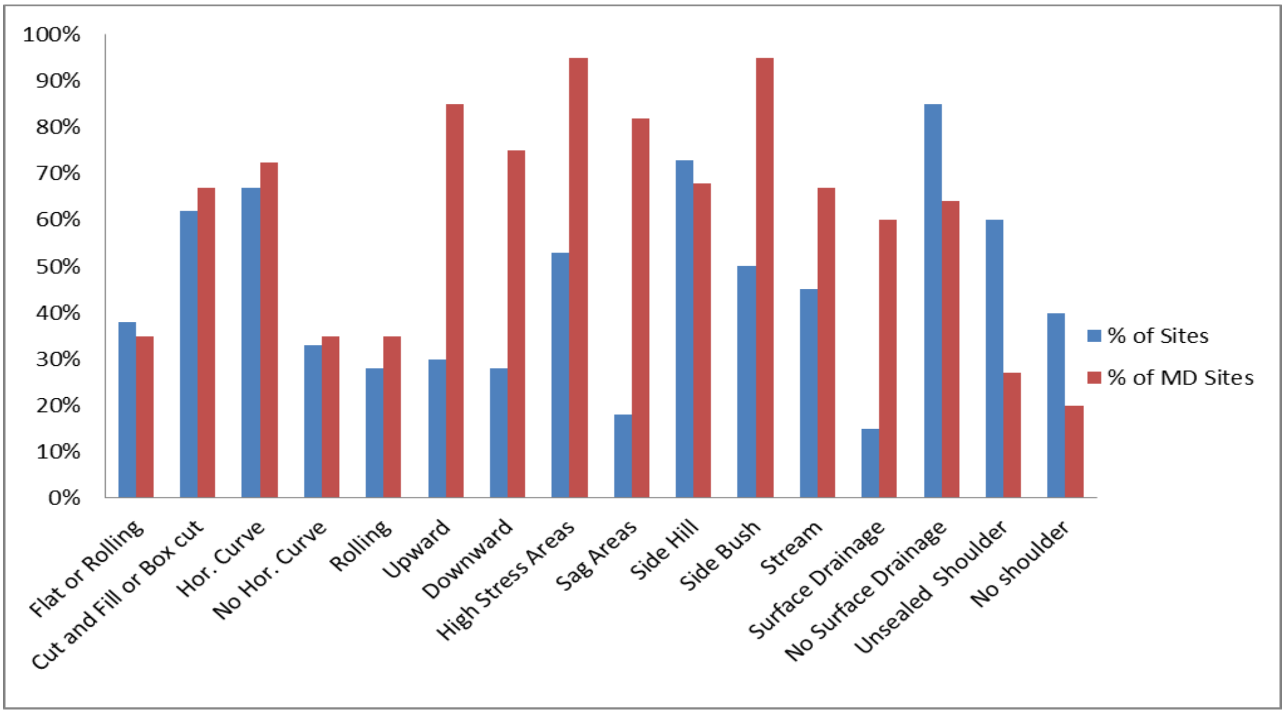


Figure 4-3 Distribution of the Factors Related to Moisture Damage

Based on the outcome of the preliminary study (Table 4-3 and Figure 4-3), it can be said that some factors have a greater effect on increasing the moisture damage risk of road sections. Road sections in cut and fill or box cut sections showed more signs of moisture damage compared to roads on flat or rolling ground. Similarly, road sections at sag curves and high stress areas were found to have increased moisture damage during the preliminary study. Moisture damage was frequently observed in road sections with side hills, streams (high ground water table), and bush areas. However, the impact of factors like surface drainage, sub-surface drainage and shoulders on moisture damage of road pavements cannot be conclusively determined (Figure 4-3). Overall the preliminary study helped to identify some possible factors and suggests further investigation during the detailed study, which will help to develop a comprehensive list of moisture damage factors for MDRA.

The factors identified during the preliminary study, presented in Figure 4-3, contribute to the varying degrees of moisture damage in different road sections. It can be observed that road sections with side hills and streams possess more symptoms of moisture damage compared to road sections on rolling ground and with low vegetation on the roadside. Almost 70% of the road sections with side hills and streams are moisture damaged sites. Although only 10% of road sections are in vertical sag areas, 90% of them are moisture damaged. Almost 100% of the road sections with a high stress horizontal curve, and with side hill or bush areas were found to have moisture damage. These factors clearly have an effect on the extent of moisture damage in road pavements. These factors have been generalised and categorised into two major groups for use as the inputs for the risk analysis.

Table 4-4 Moisture Damage Risk Factors (Classification)

Group	Sub-group (Description)
Static factors (Remain fixed or little changes over the life cycle of the road pavement)	**Geophysical Factors (G_ Risk):** These risk factors are related to geophysical and geometric features of the road section and the drainage catchment. **Pavement Profile (P_ Risk):** These risk factors are related to the pavement profile of the road section.
Dynamic Factors (These factors may change over time due to regular maintenance or renewal of the road pavement)	**Strength and Life Cycle (S_ Risk):** These risk factors are related to age of the pavement layer and strength of pavement based on FWD deflection **Drainage and Shoulder Risk Factors (DRN_ Risk):** These risk factors are related to surface and sub-surface drainage of the road pavement

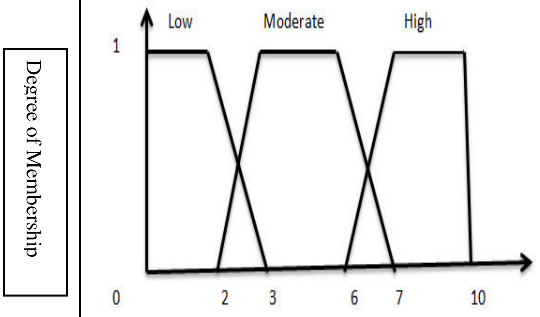
Tables 4-4 and 4-5 contain the major categories of moisture damage factors, along with the root cause of failures. These factors have been identified based on expert knowledge and experience during the field work and a rigorous literature review. These factors can be modified based on the network characteristics and conditions in the network management system.

Table 4-5 Moisture Damage Factors and Inputs for Risk Analysis

Category	Major Factors (Inputs)	Root cause/Parameter for evaluation
Static	**G_Risk** Geophysical and geometric features of the road pavement and drainage catchment (External to road pavement).	Side hill next to shoulder
		Stream within 10m
		Bush/Vegetation next to the shoulder
		High Stress/curve (Start-stop areas)
		Vertical Sag
	P_Risk Risk factors related to pavement profile (Within the road pavement).	Topography (Flat, Rolling and Sloped terrain)
		Pavement construction (Cut and fill, Box cut)
		Sensitive subgrade
Dynamic	**S_Risk** Risk factors related to materials and the strength of the road pavement.	Weak pavement layer
		Inadequate surfacing
		Old pavement and surfacing
		Materials with high PI/fines
	DRN_Risk Risk associated with drainage, traffic, climate and shoulder.	Cross fall (inadequate)
		Kerb and channel blocked, damaged
		Subsoil drain non-functional
		Rainfall high
		Water table high (1m from ground)
		Traffic volume high
		Heavy Commercial vehicle high Inadequate Shoulder

The moisture damage factors in Table 4-5 (column 2) are used as the inputs for the risk analysis. Table 4-6 below presents the membership functions and their parameters to define the inputs or moisture damage factors.

Table 4-6 Moisture Damage Factors and Related Membership Function

Moisture Damage Factors	Linguistic Expression	No of triggers	Parameters of the Trapezoidal Membership Function	Membership Function of G_Risk (Sample)
G_Risk	Low	0-1	[-3, 0, 1, 3]	
	Moderate	2-3	[2, 3, 6, 7]	
	High	> 3	[6, 7, 10, 13]	
P_Risk	Low	0-1	[-3, 0, 1, 3]	
	Moderate	2-3	[2, 3, 6, 7]	
	High	> 3	[6, 7, 10, 13]	
S_Risk	Low	0-1	[-3, 0, 1, 3]	
	Moderate	2-3	[2, 3, 6, 7]	
	High	> 3	[6, 7, 10, 13]	
DRN_ Risk	Low	0-1	[-3, 0, 1, 3]	
	Moderate	2-3	[2, 3, 6, 7]	
	High	> 3	[6, 7, 10, 13]	

The criteria presented in Tables 4-5 and 4-6 will be used to identify the moisture damage factors for use in the risk analysis. Each road section was scrutinised using the trigger based framework in Table 4-5. Based on the number of triggers, the extent (linguistic expression of the factors) of the moisture damage factors (input) can be identified. The moisture damage factors were expressed as low, moderate and high. The increase in number of triggers also increases the extent of the risk factors. In the risk analysis technique, trapezoidal membership functions were used to define the value of expressions (low, moderate and high) of risk factors. A sample trapezoidal membership function, used to define the moisture damage factors (Inputs) in the fuzzy logic model, is included in Table 4-6. The horizontal axis represents the input value for the risk analysis identified through the trigger based evaluation criteria presented in Table 4-5. The vertical axis represents the degree of membership on a scale of 0 to 1.

4.4.3 Inference Rules

The Inference rules (IF-Then) were developed based on engineering judgment, as well as knowledge and experience on the road network. Later, the inference rules were disseminated in the technical workshop. The participants were requested to form groups and provide their comments on the inference rules. The inference rules were amended based on the valuable comments received at the workshop. A total of 81 inference rules were used in the risk analysis model are presented in Appendix A. The inference rules are network specific and would need to be adjusted or developed for use on another network.

4.4.4 Risk Analysis Model (Structure)

The structure of the fuzzy logic based risk analysis model is presented in Figure 4-4. The model was developed based on the fuzzy inference system in the Matlab programme. Four inputs or moisture damage factors (G_Risk, P_Risk, S_Risk and DRN_Risk) interact together through the fuzzy inference system and present the output (MD_Risk) of the risk analysis. This model has been used for moisture damage risk analysis of a number of road sections in the network.

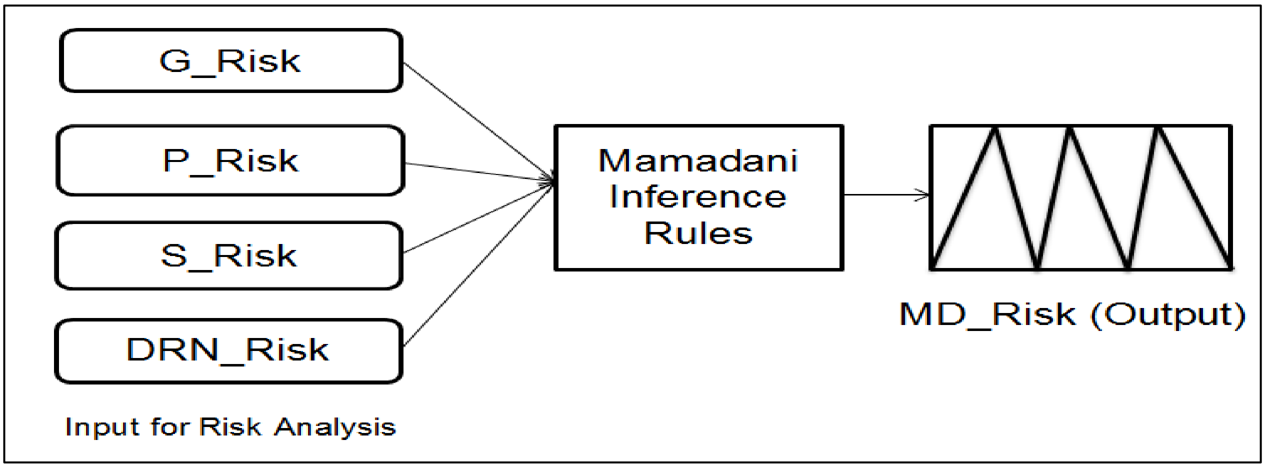


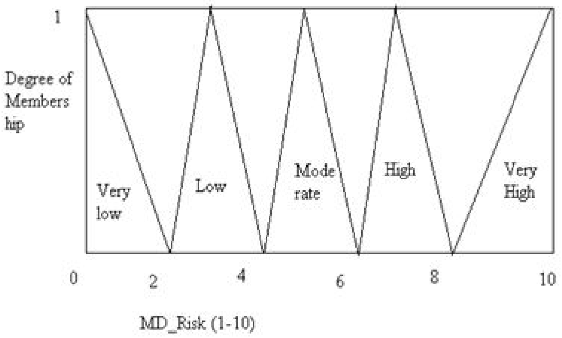
Figure 4-4 Organisation of the Fuzzy Logic Model

4.4.5 Risk Analysis Output

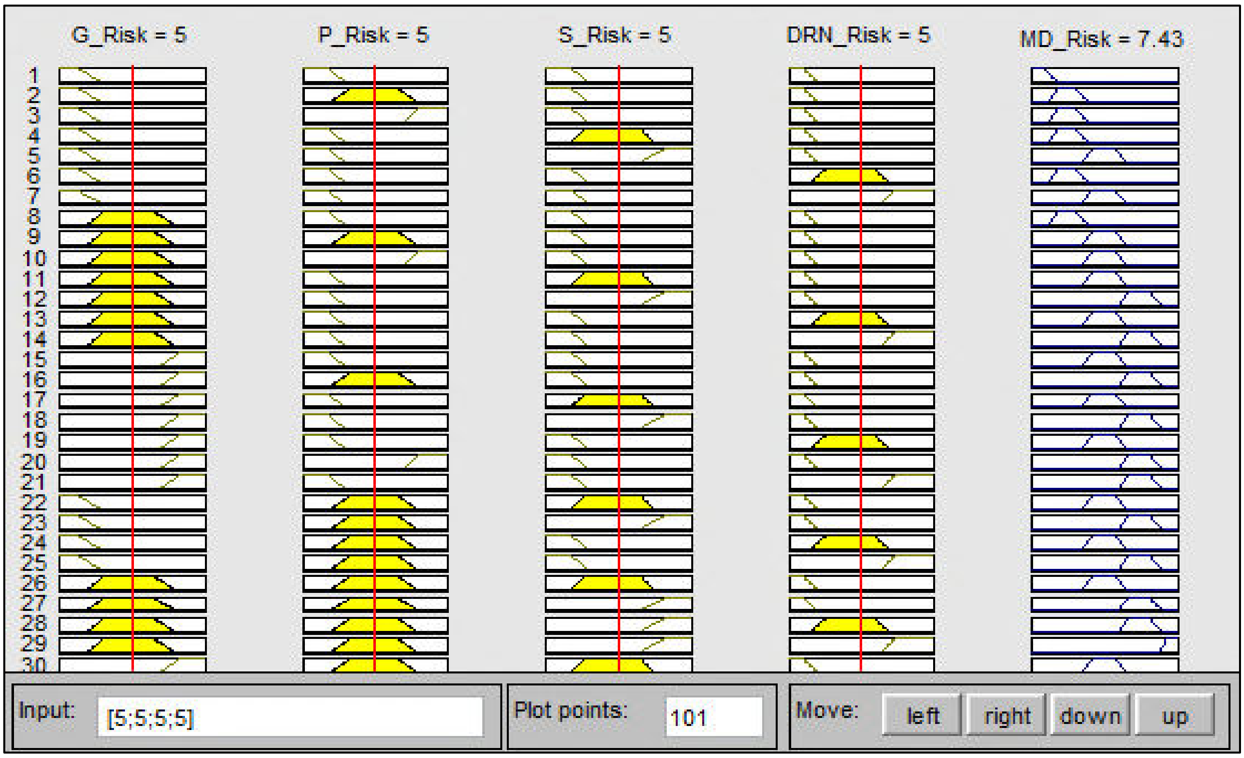
The output of the risk analysis model is perceived as a prediction or warning of moisture damage potential in a particular site. The NZTA risk assessment manual provides six tiers (negligible, low, moderate, high, very high and extreme) of risk based on the combination of likelihood and consequences of the potential threats (Transit New Zealand, 2004). Another NZTA report suggested four categories of risks such as low, moderate, high and extreme. They have also combined the likelihood and consequences of a risk scenario (Hill, Henning, Smith & Devor-Tod, 2010). The New Zealand road safety assessment program (Kiwi RAP) uses low, low to medium, medium, medium to high and high to describe the crash risks based on collective and personal risk factors (Waikato and Bay of Plenty, 2012). However, in this case the output of the risk analysis is targeted to predict any premature failure due to moisture damage.

The term MD_Risk (Moisture Damage Risk) has been used in the risk analysis model. In the fuzzy logic inference system, the output can be presented as either membership function (Mamadani) or constant (Sugeno) values. The MD_Risk is presented by a rating in the scale of (1-10) by the triangular membership function in Table 4-7. The triangular membership function incorporated five linguistic expressions (very low, low, moderate, high and very high) to predict the possibility of occurrence of moisture related damage in road sections.

Table 4-7 Moisture Damage Risk Analysis Output

MD_Risk Output	Parameters of the membership function	Likelihood of risk	Membership Function (Triangular)
Very Low	[-3,0,2]	< 20%	
Low	[2,3,4]	(20-40)%	
Moderate	[4,5,6]	(40-60)%	
High	[6,7,8]	(60-80)%	
Very High	[8,10,13]	>80%	

In the fuzzy risk analysis model, the outcome of the risk analysis can be viewed either in the rule viewer (Figure 4-5) or by the three dimensional surface viewer (Figure 4-6).



G_Risk = 5

P_Risk = 5

S_Risk = 5

DRN_Risk = 5

MD_Risk = 7.43

Input: [5;5;5;5]

Plot points: 101

Figure 4-5 MD Risk Output (Rule Viewer) of the Fuzzy Logic Model

The rule viewer (Figure 4-5) is the typical simulation output that will be used for risk analysis. There are 81 inference rules adopted in the risk analysis model. Each horizontal line in the rule viewer represents an inference rule of the risk analysis technique. It can be seen that a road section had four inputs (G_Rish-5; P_Risk-5; S_Risk-5; and DRN_Risk-5) or moisture damage factors that yielded the MD_Risk rating of 7.43 as the output of the risk analysis. So the road section is predicted to be at high risk (7.43) and the likelihood of moisture damage is within the range of (60-80) %.

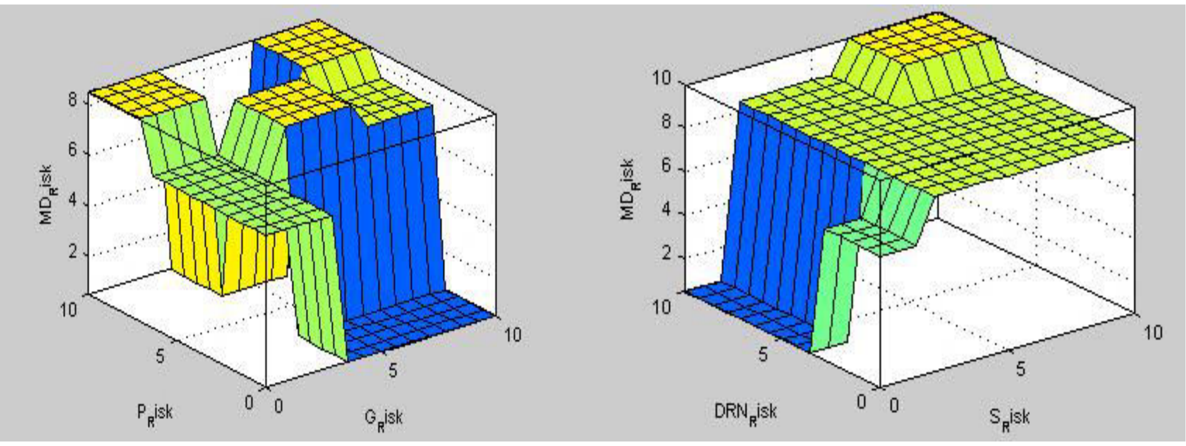


Figure 4-6 MD_Risk Output (Surface View) of G_Risk vs. P_Risk (Left) and DRN_Risk vs. S_Risk (Right)

The surface viewer (Figure 4-6) provides a three dimensional view of the contribution of the moisture damage factors in the overall MD risk. It shows the variation of MD_Risk in response to the changes in input factors. The predicted MD_Risk varies from very low to high based on the changes in the moisture damage factors (G_Risk and P_Risk) of a road section (Figure 4-7, left). The other two factors (DRN_Risk and S_Risk) are plotted in two horizontal axes, whereas the MD_Risk based on these two factors are plotted on the vertical axis. This surface viewer is more applicable for graphical representation of the moisture damage factors and MD_Risk of the model.

4.5 Application of Fuzzy Logic Model (Case Study)

The generic model has been used in this case study to identify the moisture damage risk (MD_Risk) of 100 road sections (100 m length) of different sites in the network. The database of road sections used in the preliminary study was used to train the risk analysis model. During the training process some anomalies were observed mostly related to the membership functions and the inference (If-Then) rules. Some of the membership functions and inference rules were adjusted during the training process. Once the model was well trained, the 100 road sections were analysed to predict the moisture damage risk. Each site was scrutinised through the risk analysis model. Figure 4-7 shows the variation of MD_Risk (output) and the moisture damage factors (inputs) of 13 road sections of one site in the case study.

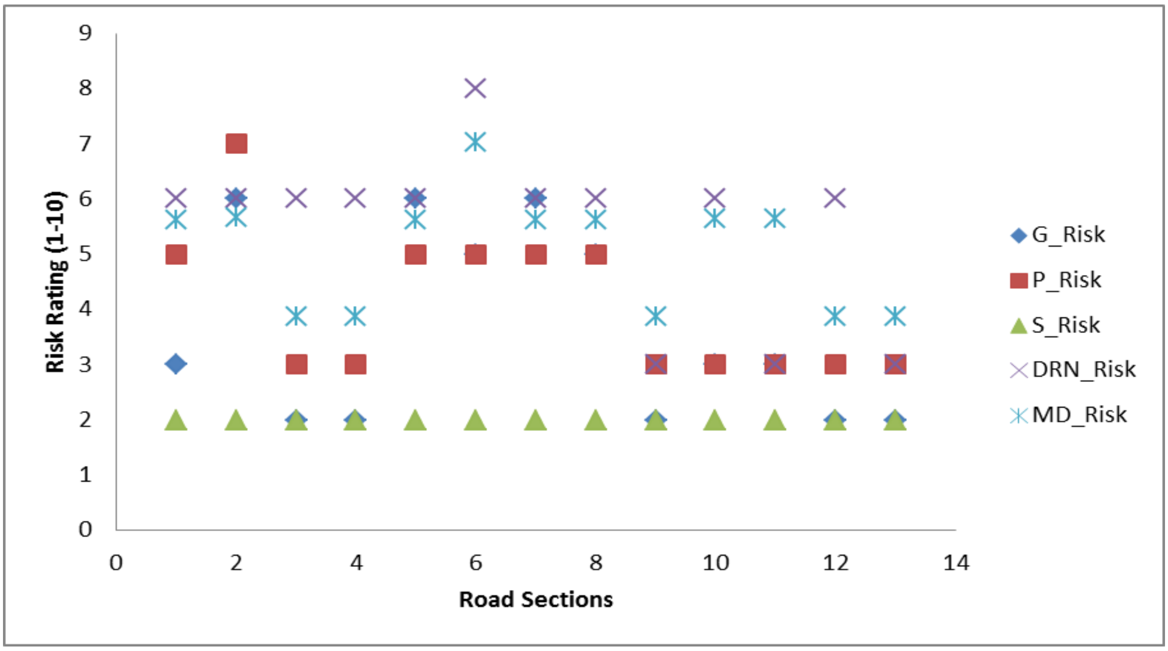


Figure 4-7 Distribution of Risk Factors and MD_Risk

Moisture damage factors (inputs) of 13 road sections have been plotted (Figure 4-7) along with the MD_ Risk (Output). The vertical axis is the MD_ Risk rating and the horizontal axis is the road section numbers. The S_Risk (Strength) and DRN_Risk (Drainage) factors are constant in all of the road sections. The geophysical (G_Risk) and the pavement-related (P_Risk) factors of the road sections vary considerably. These two factors have contributed to the MD_Risk rating of the road sections. The MD_Risk of all these (100) road sections followed a similar pattern (Figure 4-8) to the moisture damage factors (G_ and P_Risk).

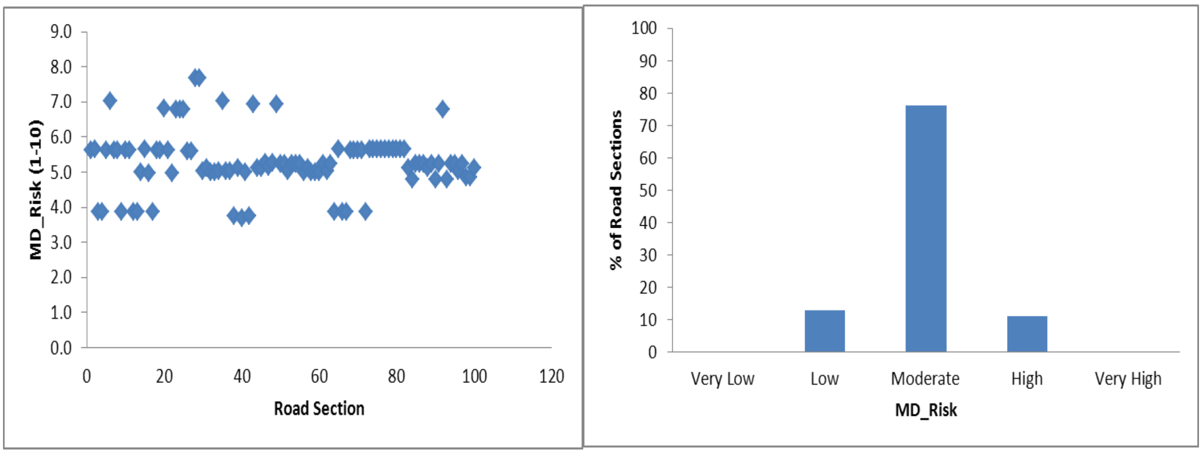


Figure 4-8 Distribution of MD_Risk of the Road Section (%)

In Figure 4-8, the predicted MD_Risk is plotted on a scale of 1 to 10 (Rating). The higher the rating means the higher the potential for moisture damage of the road section. The percentage of road sections in each of the MD_Risk categories has been plotted as well. The MD_Risk of these road sections were identified within the range of 4 to 8. This indicates that the road sections are in the range of low to high risks of moisture damage. Almost 76% of the road sections have been identified to be at moderate risk, whereas only 11% of the road sections are at high risk of moisture damage. None of the road sections have been identified to be at very high risk. The road sections analysed in this study will continue to be monitored in the future to identify their actual performance both in dry and wet weather conditions. Performance indicators such as rutting, roughness, flushing, and texture of the road sections will be monitored at regular intervals. MD_Risk obtained from the risk analysis model and the average lane rutting of a number of road sections of a particular site were plotted in Figure 4-9.

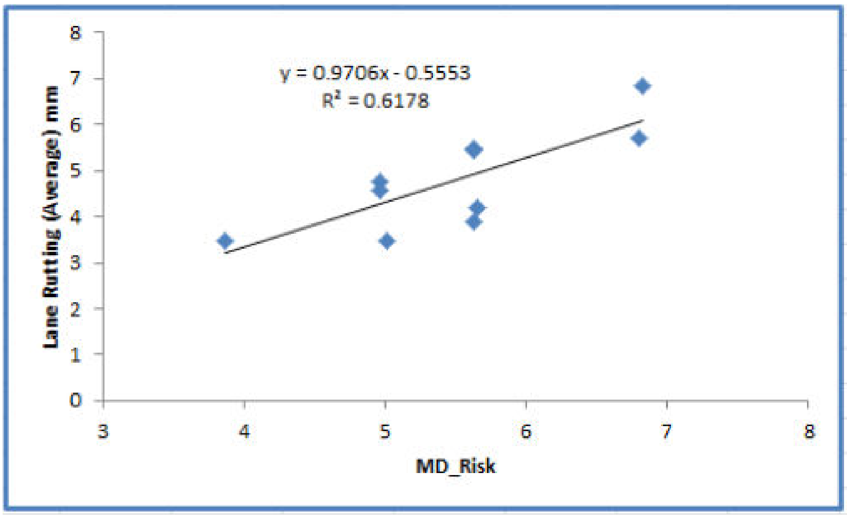


Figure 4-9 Correlation of Lane Rutting and MD_Risk of a Site

Rutting is one of the performance indicators of flexible road pavements in New Zealand and moisture has been considered as one of the reasons for permanent deformation especially in the subgrade layer. The average lane rutting of 100 m road sections of a site were plotted against their predicted MD_Risk (Figure 4-9). The average lane rutting of the road sections had good correlation ($R^2 = 0.6178$) with the MD_Risk rating predicted by the risk analysis model. Further research will be continued to identify the relationship between the moisture damage (MD_Risk) risk and other performance indicators of the road pavement. These will help to validate the application of the risk analysis model. The proposed validation method was also presented in Chapter 3 and in Mia et al. (2013, 2014).

4.6 Summary

Moisture is considered as one of the major deteriorating factors of flexible road pavements. It has a significant impact on road pavements in New Zealand. Most of the roads in New Zealand are built as flexible granular pavements. The presence of excess moisture is one of the major causes of premature failure and a reduction in the level of service of road pavements. The damage caused by moisture in road pavements has some severe consequences, including expensive renewal, heavy maintenance, wet road crashes, injuries and fatalities. These consequences are borne by the road controlling authorities and the travelling public. Now these risks are partially transferred to the contractors or management organisations, especially in networks managed by performance-based contracts. Consequently, contractors have to be proactive in predicting the major risks, including moisture damage in the road network. In this regard, a moisture damage assessment method has been formulated to identify the sections of a road network that are at high risk of failure.

The proposed risk analysis model is part of a wider risk assessment method. The model has been developed using the fuzzy inference system in Matlab. A generic risk analysis model has been developed based on the knowledge and expertise gained during the field work and from the literature review. The generic model has been adjusted and further developed based on the feedback gained from a technical workshop. Then the risk analysis model was used to identify the moisture damage risks of road sections selected from the road network. The risk analysis model is easy to use, accommodates the use of the linguistic expressions of risks and predicts the risk (possibility) on a scale of 1 to 10. The risk rating can be used to identify the consequences of moisture damage in a road network both at tender-bidding and implementation stages. The model can be useful for road controlling authorities or contractors to assess the moisture damage risks of the road network. Based on the risk analysis the road controlling authorities can adopt proactive drainage measures, especially the installation of proactive drainage, pavement profile correction, resurfacing and rehabilitation. In chapter 9, the application of the risk analysis model will be validated through long term evaluation of the performance indicators of road pavements. Although the model is network specific, it can be utilised for other road networks with sufficient adjustments of the membership functions and the inference rules.

Chapter 5: Application of FTA in MDRA

5.1 Introduction

This chapter aims to develop, and subsequently demonstrates, a risk analysis method to identify the moisture damage potential in flexible road pavements using the FTA technique. There are two steps in the adaptation of the FTA technique for use in this application. The first step is to identify the failures due to excess moisture and their root causes. The second step is to develop the fault tree based on the relationships between the root causes of failure. The developed fault tree can then be used to measure the risk using a qualitative or quantitative approach (Burhan, 2010). The qualitative risk assessment helps to identify the potential causes of any premature failure in the road pavement. The quantitative risk analysis involves the adaptation of a prediction method to identify the probability of failure at different stages of the life cycle of the road pavement.

5.2 Background

FTA was developed at Bell Laboratories in 1962 by H.A. Watson, a part of the United States Intercontinental Ballistic Missile control system (Halme and Aikala, 2012). It is one of the most commonly employed techniques to develop a causal relationship between the failure and root causes in risk and reliability studies. In general, FTA is a failure scenario analysis system where the probability of an undesired event is determined through a combination of root causes based on Boolean logic (AND-OR) (Halme and Aikala, 2012; Patil et al., 2009). This analysis technique is usually applied to identify the risk of failure in manufacturing and processing industries, thereby increasing the reliability of any preventative system in place. In the manufacturing and process industries, reliability is often vital and even minor faults can hamper the reliability of any system. The term reliability is defined as the probability that any process or system will perform the desired functions without any interruption or failure for a certain period of time (Patil et al., 2009).

FTA essentially identifies the risk of any failure or occurrence of the undesired event in any process. Any failure in a manufacturing or process system hampers the production and also affects the life cycle cost. Patil et al. (2009) presented an FTA based reliability analysis of a Lathe machine used for manufacturing of small tools and machine parts. This study attempted to correlate the effect of any undesired event in the life cycle of the machine through FTA. The failure risk assessment of the machine was conducted using both qualitative and quantitative approaches. Some of the root causes identified included blunted tool, improper speed, wear and tear, loose mounting, improper cooling time and improper alloying. Anyone, or a combination of these root causes, may induce the incident of the machine being broken or out of use. The probability of the failure (machine broken) was estimated using the Boolean logic in the FTA and the probability of failure P(F) and the reliability R, of the machine were calculated using Equations5-1and 5-2 (Patil et al., 2009).

$$\text{P (F)} = \mathbf{1 - [(1 - \boldsymbol{V}1)(1 - \boldsymbol{V}2)(1 - \boldsymbol{V}3) \ldots\ldots (1 - \boldsymbol{Vn})]} \qquad \textbf{Equation 5-1}$$

Where n= Number of Root Causes

V= Probability of failure of root events (1, 2, 3.....n)

$$\text{Reliability R} = [\mathbf{1 - \boldsymbol{P}(\boldsymbol{F})}] \qquad \textbf{Equation 5-2}$$

Where *P (F) = Probability of Failure*

FTA utilises Boolean logic (AND/OR) to develop the vulnerability assessment through outlining the relationship between the low probability/high consequence system failure, and the higher probability/low consequence primal event (Lapp, 2005). FTA has some added advantages compared to some other risk assessment techniques such as its ability to focus and process multiple levels of interaction among the sub-systems and root causes. The risk assessment technique can incorporate any (short and long) time frame for analysis. The backward analysis of the top event down to the root causes can provide a proactive maintenance approach to prevent any failure in the system (Lapp, 2005).

The FTA technique has also been successfully applied in various construction and project management sectors. Swarna and Venkatakrishnaiah (2014) used FTA in construction risk assessment. Construction project risks in terms of cost, time and quality were examined using the Boolean logic based FTA. The root causes of the three different risks were associated to develop the fault trees. The probabilities of these three risks were estimated using both the qualitative and quantitative approaches. Equation 5-3 shows the distribution used for probability calculation of any undesired event in terms of cost, time and quality.

$$\boldsymbol{f\ (k, \lambda) = \lambda^{k} e^{-\lambda} / K!} \qquad \textbf{Equation 5-3}$$

Where f (k, λ) = Probability mass

If Poisson distribution with parameter, λ>0, K= (1, 2, 3, … n)

A random variable X can be exemplified by the Poisson distribution with parameter λ. If λ>0 and k is a positive integer, then probability mass f (k, λ), can be estimated using the Equation 5-3. The value e is 2.71828, and K! is the factorial of k. The outcome of the study indicated that the 'risk estimation' can be correlated with the maintenance framework to reduce any future risk of cost, time and quality (Swarna & Venkatakrishnaiah, 2014).

A similar study to this current research was conducted by Schlotjes et al. (2014). They demonstrated the development of a risk-index-based diagnostic framework that can be used to predict rutting, cracking and shear failures in road pavements. A generic pavement failure path was used as the basis for understanding the failure and their root causes. Construction quality, pavement design, environment, subgrade properties, poor pavement support and traffic were the major causes of rutting, cracking and shear failure. Fault trees for these failures were developed based on the knowledge gained through the literature review and the field work. This study evaluated the applicability of FTA and support vector machine classification technique for the estimation of the pavement failure risk due to rutting, shear and cracking. Both of these techniques proved to be strong candidates for this application.

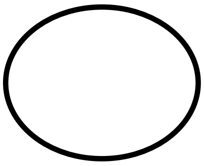
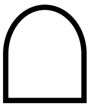
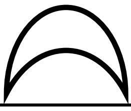
The above brief review has confirmed that FTA has been widely utilised in the risk assessment of various sectors, especially in the manufacturing and process industries as well as construction management. The application of FTA in road network asset management is comparatively new, although similar work was undertaken to demonstrate the development of a diagnostic approach in pavement failure risk assessment.

5.3 Development of the Fault Tree

The development of the fault tree in moisture damage risk assessment is crucial and needs an extensive knowledge basis, both from the literature and experience of working on the network. During the course of the research, the literature review and three years' worth of field work on the network assisted in identifying the major failures, their root causes and relationships (Mia et al., 2013, 2014; Mia, Henning, Costello & Foster, 2015). Recent works on moisture damage to pavements in New Zealand (Hussain et al., 2011; Schlotjes et al., 2014) were also helpful in formulating the fault trees.

FTA is a failure-scenario analysis technique in which the occurrence of an undesired event is evaluated through deductive reasoning of the root causes based on Boolean logic. It is primarily applied to identify how any system can fail and how to reduce the risk of failure by eliminating or controlling the root causes (primal events). The fault tree is composed of Boolean (AND-OR) logic based diagrams that demonstrate the state of the system. The analysis begins with the identification of any potential undesired top event that may hamper the production or induce system failure, and finishes with the fundamental prime events. This chain of events is correlated through the AND-OR based logic and usually the probability of the top event can be estimated based on the probability of primary events (Burhan, 2010; Swarna and Venkatakrishnaiah, 2014). The basic building blocks used in the development of the FTA in this study are presented in Table 5-1.

Table 5-1 Basic Building Blocks of any FTA (Burhan, 2010; Lapp, 2005)

Types of Event and Gate in FTA	Symbols	Features
Top Event		Low probability and high consequence undesired event that is usually caused by a number of primary events
Primary Event/Root cause		Basic root cause of any significant failure
AND Gate		A top undesired event occurs if all root causes are present concurrently
OR Gate		A top undesired event occurs if any of the root causes are present

Often, this ‘AND-OR’ logic based fault tree is applied in the control system’s risk assessment, especially in electrical units that are prone to failure due to the functioning of any component or control gate (Lapp, 2005). To explain the AND-OR logic based FTA, a simple fault tree is demonstrated that shows how a fire hazard occurs due to the root causes in Figure 5-1.

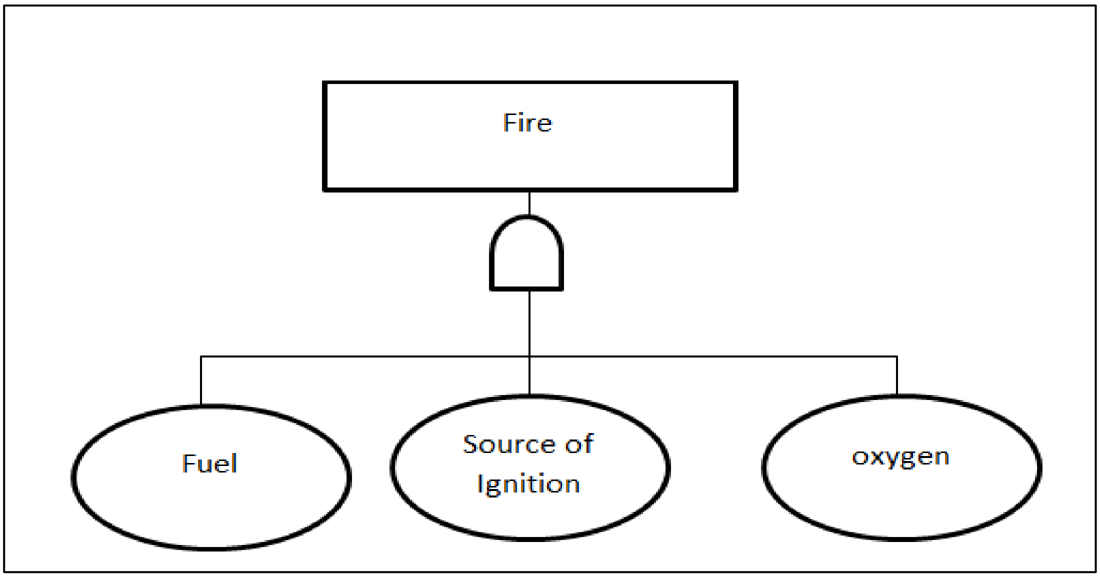


Figure 5-1 FT of Fire Hazard (Burhan, 2010)

The FT of fire hazards shows a simple AND logic based correlation between the fire hazard and its root causes. The AND logic gates indicate that fire cannot occur without the presence of any of the three root causes, i.e. fuel, a source of ignition and oxygen/air. Therefore, the probability of the fire hazard is likely to be low, as all three factors or causes need to occur concurrently. The probability of the occurrence of fire is the product of the probabilities of the root causes.

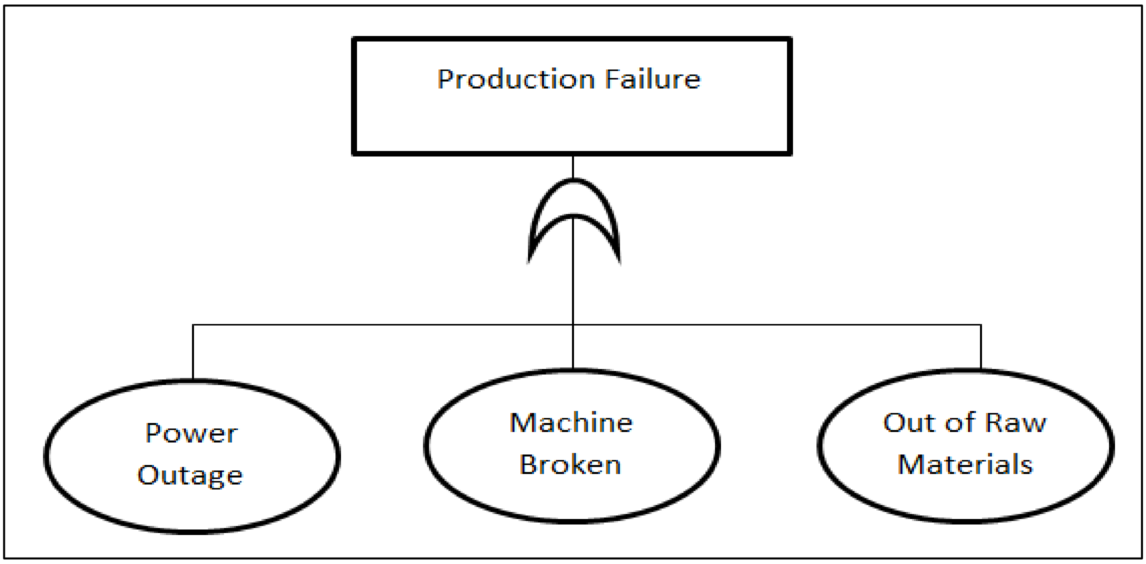


Figure 5-2 FT of Production Failure of any Plant (Burhan, 2010)

Whereas, in Figure 5-2, the FT of any failure in production may be caused by any of the root causes. The power outage, broken machine or lack of raw materials can hamper the production. Based on Boolean logic, the probability of the production failure will be the aggregate of the probabilities of the root causes in Figure 5-2.

5.4 Types of Moisture Damage Risk and Formation of the FT

Pavement distresses can be either directly or indirectly caused by the presence of excess surface and sub-surface moisture in road pavements. The root causes of pavement distress are classified into four categories as follows (Austroads, 2009);

- Climate (temperature, rainfall);
- Traffic loading (axle configuration, tyre pressure, heavy commercial vehicles);
- Inadequate base or sub-base layer, including material quality; and
- Effect of moisture (excessive moisture, seasonal variation).

Moisture, one of the above factors, affects the road pavement in two different ways. When a road pavement is rehabilitated, the first types of distress are observed at the surface layer in the form of potholes, stripping, heaving and edge break. These early pavement failures or distresses in this region can be caused due to the presence of moisture in combination with poor quality materials or poor construction practices. Over time, due to increased traffic loading and seasonal fluctuations in climate and moisture levels, the lower pavement layers (base and Sub-Base) deform and ultimately cause failures, such as rutting, shoving, cracking, ravelling and shear in the road pavement (Austroads, 2009). The moisture damage in the road pavement can be separated into two typical categories, namely early pavement damage and permanent pavement damage. These two types of damage were considered for this study and the related fault trees were developed for risk assessment. Both types of pavement damage are discussed in turn in the following sections.

5.4.1 Early Pavement Damage

Early pavement damage occurs in the surface layer and is usually observed within the first seal cycle (7 years) of the road pavement. The types of distresses that are considered as early pavement damage are stripping, heaving, pumping, potholes and edge-break. Although these pavement distresses occur in the surface layer and can be treated with minor repair/reseal works, they indicate the beginning of moisture related issues in the pavement. Any road section showing early pavement damage can be considered at risk of premature failure. Hence, the maintenance strategy can be developed based on the risk assessment of the road network. Figure 5-3 shows the FT developed to assess the risk of premature failure of newly rehabilitated road sections within the first seal cycle. Road sections are typically resealed on a cycle varying between 7-10 years, depending on the surface condition. The FT has been formulated to demonstrate the root causes and their relationship in developing early pavement damage in road pavements.

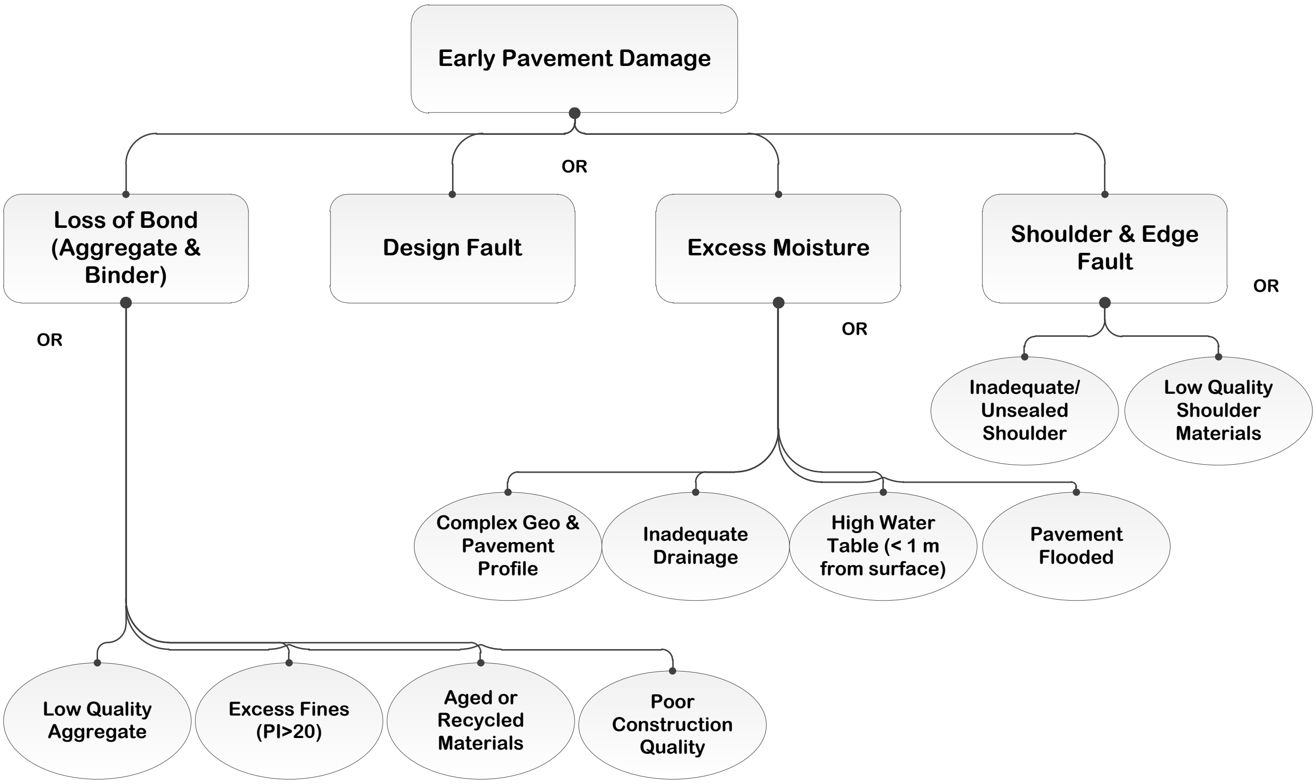


Figure 5-3 Fault Tree for Early Pavement Damage in Road Pavements

Referring to Figure 5-3, the loss of adhesion between the aggregate and binder, excess moisture, shoulder and edge defects and any flaw in design have been considered as major (intermediate) factors for failure in road pavements. Low quality materials, excess fines in the pavement, older pavements and poor construction quality may be the reasons for the loss of bond between the aggregate and binder. Excess moisture in pavements can be linked to a deficiency of drainage, high water table, or obstructions in drainage due to a complex geophysical and pavement profile in the road section. Flooded road sections can also cause a sudden increase of moisture level in the pavement formation. Any road section recently rehabilitated can encounter these root causes at early stages and induce the types of early predicted damage. The root cause and intermediate factors are connected by ‘OR’ logical gates because any of these causes can induce the occurrence of a fault or damage at that early stage of the road pavement.

5.4.2 Permanent Pavement Damage

The permanent form of moisture damage is predominantly structural failure and requires either stabilisation or a dig-out repair to reduce the risk of further expensive repair or failure. Often, road sections of high risk of moisture damage, show early signs of failure and eventually end up in calling for structural rehabilitation or renewal of the pavement. Figure 5-4 shows the FT that was conceptualised to identify the root causes of the permanent failure in road pavements due to excess moisture. The major factors or causes of permanent pavement damage in the fault tree in Figure 5-4 are;

- **Subgrade Failure:** Excess fine materials in the subgrade often make it sensitive to moisture. Consequently, when the moisture exceeds the equilibrium moisture level the moisture sensitive subgrade reacts and the resulting expansion causes subgrade failure (Arampamoorthy & Patrick, 2010). Thus the lack of support for the base and sub-base induces catastrophic failure of the pavement layer.
- **Pavement Layer Failure:** Either low quality base or sub-base materials, unbound layer (absence or lack of cement, lime or foamed bitumen) or excess fines coupled with excess moisture can cause disintegration of the pavement layer. The pavement layer can fail at an exponential rate over time due to these factors (Henning et al., 2009). The factors are linked with an ‘OR’ logical gate because any of them can cause pavement failure.
- **Drainage Catchment Effect:** The geophysical characteristics of the road section may affect the level of moisture in the pavement formation. In particular, a side hill next to the pavement coupled with vegetation may hinder the removal of the surface water. In addition, a water source (especially springs, perched water table, artesian structures) in close proximity to the road pavement may also increase the amount of moisture in the pavement (Patrick et al., 2014).
- **Moisture in Pavement Formation:** Road pavements are constructed to counteract the adverse effect of moisture. However, with time the level of moisture may increase and hamper the integrity of the pavement leading to permanent deformation. A lack of surface drainage or sub-surface drainage, a high water table, or inadequate shoulder may all be possible causes of this increase in moisture.

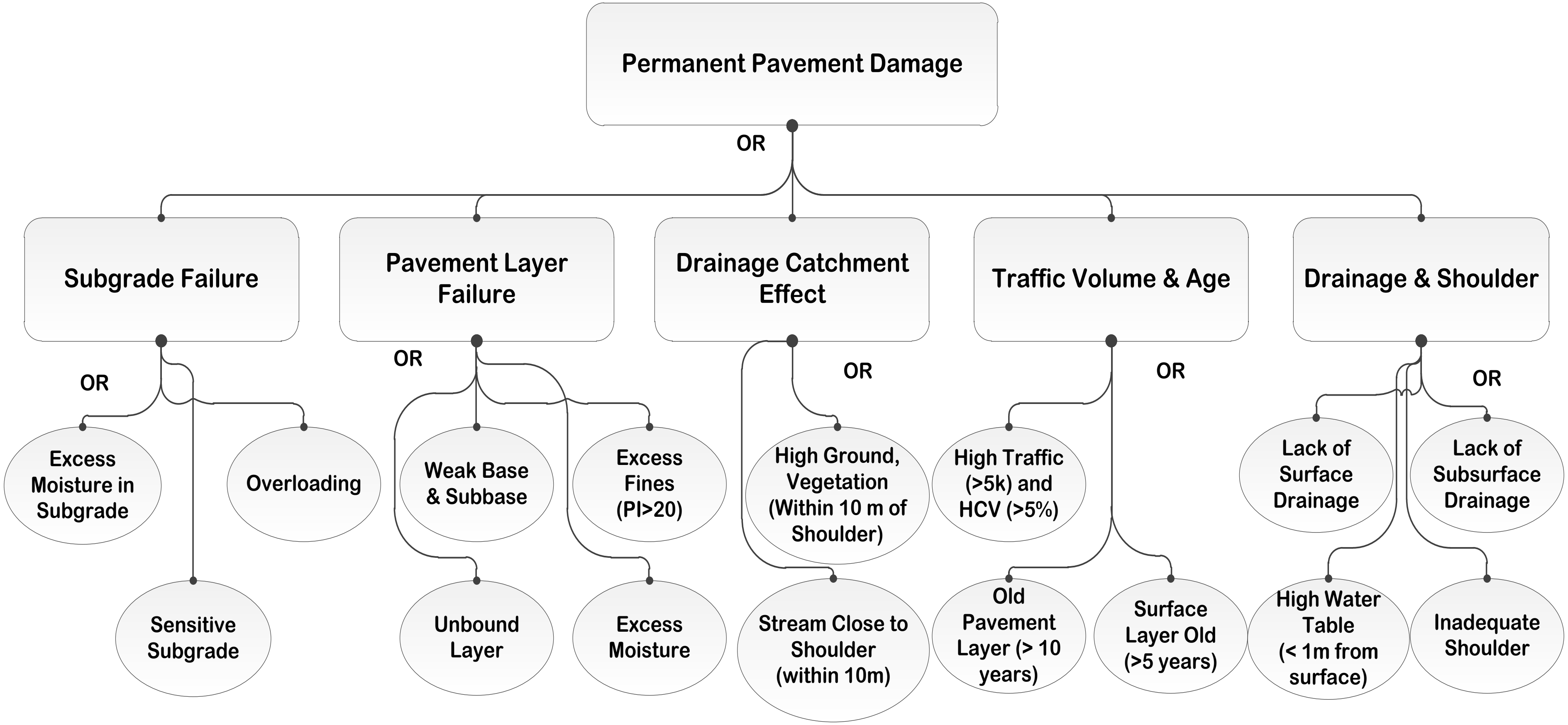


Figure 5-4 Fault Tree for Permanent Pavement Damage in Road Pavements

- **Traffic Volume and Age of Pavement:** Traffic loading has an adverse effect on the pavement structure. If the quantity of heavy commercial vehicles increases, then the risk of failure also increases due to the accumulation of damage caused by the axle loading. Both the pavement and surface layer become vulnerable due to repeated failure over time. Thus the age of the pavement and surface are considered to be factors in predicting the risk of moisture damage (Henning, Alabaster, Arnold & Liu, 2014).

The FT developed for permanent damage in the pavement (Figure 5-4) includes a wide variety of factors or root causes that are linked together to identify the vulnerability of any road section. The fault trees were developed based on the generic fault tree developed by Schlotjes et al. (2014). Here, the ‘OR’ logical gates are mostly used for the FT, because the factors are mostly unique and any of the root cause can induce damage in the road pavement. There is certain inclusiveness or overlapping of root causes, especially the presence of excess moisture in the pavement (base, sub-base and subgrade). The theory and methodology adopted by Schlotjes et al. (2014) and Burhan (2010) were considered for probability calculation and estimation of the risk of pavement damage. The next step is to apply the developed FT in assessing the moisture damage risk of road sections in a network.

5.5 Application of FTA in Moisture Damage Risk Assessment

The FTA technique was evaluated on the basis of risk appraisal of road sections in one of the road networks in New Zealand. The road sections were obtained from the West Waikato (South) road network. The road sections selected for the case study were targeted to demonstrate the risk assessment approaches. Road sections selected for the qualitative risk assessment were predominantly rehabilitated within the last 7-10 years. These sites were showing substantial symptoms of moisture induced damage (both early and permanent) in road pavements.

Some of these road sections were recently rehabilitated and could be used to quantify the probability of failure at early stages of the pavement. The road sections were either physically surveyed or assessed through the video survey. The pavement and surfacing information were obtained from the road asset management database. The drainage condition data were obtained from T-Drain, a contractor’s dedicated web based database of the road network. FWD and test pit data (Scala Penetrometer) were used to assess the strength of the pavement. Test pit reports were also used to evaluate the pavement layer structure and sub-surface moisture condition of the road pavement. The combined dataset was used to identify the presence and extent of the root causes in the fault trees that eventuality lead to the probability of any failure due to moisture damage.

5.5.1 Qualitative Assessment

Qualitative risk assessment through FTA can identify the failure paths showing the root causes and their association in case of a premature failure. Usually, the road pavement is designed for 25 years with two reseal cycles planned to maintain the texture, skid resistance and water tightness. Regular maintenance of road pavements is required to repair potholes, edge break, high or low shoulders and to control vegetation on shoulders. If the road pavement shows excess wheel path rutting, ravelling and cracking then it is repaired by stabilisation patches. As the number of stabilisation patches on a road section increase over time within the first seal cycle, it becomes impractical to repair it, rather it requires rehabilitation.

Two road sections were chosen for this case study. Both of these road sections were rehabilitated in 2006 and again in 2011. The maintenance costs of the road section increased significantly during the last two to three years. There had been a number of stabilisation patches in the road sections. They were therefore considered to have failed prematurely. The distress mechanisms ranged from surface flushing, stripping and ravelling to pavement deformation (excess rutting and depressions). The road sections were regularly monitored and, recently, they were selected for forensic investigation to identify the causes of the premature failure. The road sections were inspected to identify the pavement distresses and surrounding features that may have induced the distresses. Test pits were dug at different locations where road pavements were showing excessive rutting and signs of shear failure. Some test pits were dug in the areas where the pavement condition was satisfactory, and the stabilisation patches were performing well. This was helpful to compare the sub-surface conditions of different road sections. Some preliminary observations helped to identify the test pit locations in the road section. The observations are summarised below;

- There were a combination of reasons for premature failure;
- Rutting and flushing were the predominant failures. Rutting was not uniform and seems to be mostly due to the deformation of the base course;
- Site geography was complex with high side hills, a large stream nearby and vegetation blocking the drain;
- There were a number of sag areas and transition points of horizontal and vertical curves. Water usually settles in these areas for long periods;

- There were a number of high stress areas with high volumes of heavy commercial vehicles. Most heavy commercial vehicles use this road to bypass the nearby towns;
- Design and construction methods might have affected the integrity of the pavement layer. The existing pavement layer was overlaid in 2011 on top of the old pavement layers. The pavement layers were in-situ stabilised in 2006. Thus, the old pavement layer (2006) is the new sub-base layer which may not have been adequate to carry the load from the new overlay (2011). This may be the cause of widespread rutting in the road section. In addition, the level of moisture in the pavement varies significantly so the rutting in the road section is not uniform;
- Stagnant water was visible in some areas (even in the dry season) on the road section;
- Manholes were mostly dry with one manhole found wet, as was the subsoil connection, indicating that it was functioning; and
- Pavement profile seemed to be inadequate to facilitate draining, especially due to irregular settlement and widespread moisture damage. Road pavements were too flat and may cause aquaplaning due to excess rutting at some points.

The test pits were useful in detecting the root causes of failure in the road pavements.

Figure 5-5 exhibits a specimen test pit of the worst performing site based on the level of rutting.

(a) (b) (c) (d)

Figure 5-5 Test Pit at the Worst Performing Road Section

The test pit condition indicated that the pavement (Base) layer was wet, soft and unbound and the lower sub-base layer was nearly saturated. Figure 5-5 exhibits a specimen test pit of the worst performing site based on the level of rutting. Figure 5-5 (a) was the cylindrical specimen of pavement layer extracted from the test pit and the Figures 5-5 (b) and (c) indicated the conditions of the different layers. The Figure 5-5 (d) showed the condition of subbase layer which is almost saturated and reverted back to granular due to lack of cementation in this layer. The test pit condition indicated that the pavement (base) layer was wet, soft and unbound and the lower sub-base layer was nearly saturated [Figure 5-5 (b, c and d)]. The road sections were treated with an overlay in 2011 and moisture in the base layer was trapped due to the presence of the old seal layer underneath. Inadequate support provided by the sub-base layer may have caused the excess deformation of the pavement layer.

The road sections were in regions of complex geography with side hills, high vegetation on the roadside and with a large stream in close proximity to the road pavement. The road pavements are mostly in cut and fill and have a history of flooding. Overall, the road sections are among the most complex sites in the network, and the pavement distresses and test pit condition indicate the road sections are close to premature failure. Although there were sub-surface drains installed during the last rehabilitation, they were not adequate. In addition, the shoulder was unsealed and inadequate in most places in the road section. All of this information was helpful in evaluating the sites using the fault trees in Figure 5-3 and 5-4. The FT in Figure 5-6 shows the root causes of the failure of the road section based on the outcome of the forensic investigation. The root causes in the failure paths are shaded in grey.

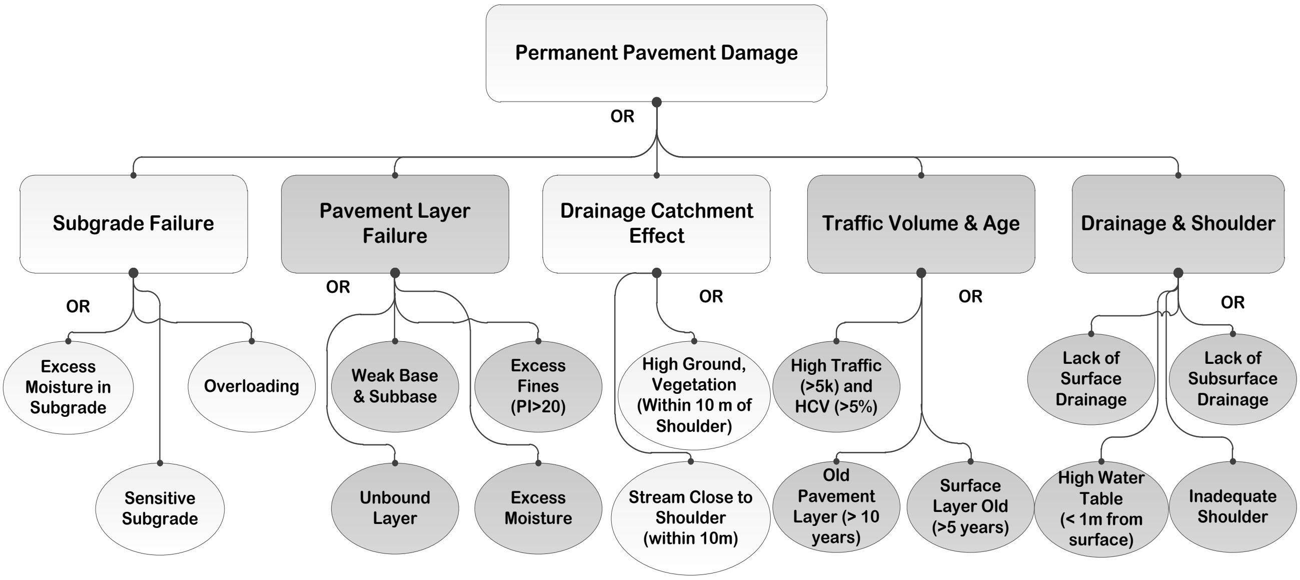


Figure 5-6 Fault Tree Showing the Critical Failure Path (Root Causes in Grey Shed)

The FT in Figure 5-6 shows that the road sections failed because of the weak pavement layer, the effect of the drainage catchment and the excess moisture in the pavement formation. These factors were then related to their root causes which might have a differential level of impact in causing the pavement damage. Once root causes are identified, road controlling authorities can focus on developing both the short and long term remedial measures. In this case, the geography of the site cannot be modified so little can be done to change the static moisture damage factors. Rather, it would be more practical to improve the dynamic moisture damage factors such as pavement strength and drainage. If the road pavement was rehabilitated again without adequate drainage to eliminate the moisture related problems, it will almost certainly fail again. The potential long term solution is to remove the existing base layer along with the old seal layer and replace with a good quality sub-base and stabilised base layer. As the water table is high, allowance should be made to mitigate excess moisture in the road pavement. Thus the FTA can be essential in investigation of road pavements to identify the causes of premature failure and the remedial action to counteract against the potential causes of failure.

5.5.2 Quantitative Assessment

The quantitative risk assessment through FTA can be applied to identify the future probability of occurrence of the undesired event or risk. Newly rehabilitated road pavements are at risk of premature failure. Often, this premature failure begins with the symptoms of moisture damage. The concept of early pavement damage and permanent pavement damage can be used to quantify the probability of premature failure of any road section due to moisture damages. This form of risk assessment is essential in determining the vulnerability of the road network and in short and long term planning of the maintenance programme in the network.

There are a number of ways to quantify the probability of occurrence of early and permanent pavement damage in the road pavements. A number of proprietary FTA software programmes are available, especially for the reliability assessment of manufacturing and process industries. In this study, an online program was selected to identify the probability of any top undesired event based on the probability of the root causes. A fault tree was developed (Figure 5-7) to identify the risk of Early Pavement Damage (EPD) of any road section within the first five years of renewal using the online programme.

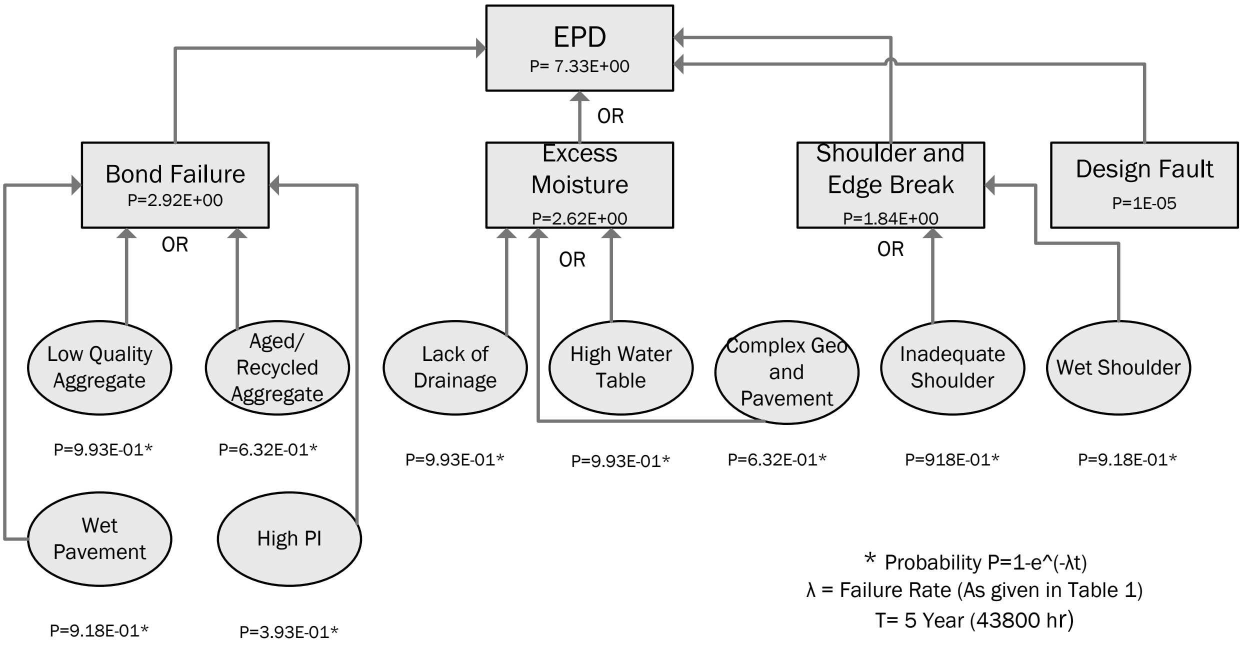


Figure 5-7 Online FTA to Calculate the Probability of Early Pavement Damage[1]

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[1] Output of the FTA using the free online fault tree analysis software developed by ALD:

Referring to Figure 5-7, the top event in the FTA is the occurrence of Early Pavement Damage (EPD).The probability of occurrence is time dependent and calculated for a time frame of 5 years (43,800 hours). Three 'OR' based logical events (bond failure, excess moisture and shoulder & edge fault) and one constant probability event (design Fault) precedes the top event. The four major logical gates and their successive root causes are linked in the fault tree of the programme. The root events generate the probability of the intermediate events based on the 'AND-OR' based calculation method demonstrated in the literature (Burhan, 2010; Halme & Aikala, 2012; Swarna & Venkatakrishnaiah, 2014). The probability of root events is assumed to be 'evident', 'time-dependent' and estimated using Equation 5-4.

$$\boldsymbol{Probability\ of\ Events\ P = 1 - e^{-\gamma t}} \qquad \textbf{Equation 5-4}$$

Where γ = Failure Rate (Estimated based on experience on the frequency of surface and pavement failure in the network);

t = Analysis period (5 years for moisture damage risk analysis in road pavements).

The output of the probabilistic analysis of the online fault tree is presented in Table 5-2 and Figure 5-7. The failure rate of the root events was estimated based on the experts comment on failure or faults due to the root causes in the root event. The failure rate can be identified through condition surveys or performance analysis data as well. The failure rates of the root causes have to be adjusted across the state highways and networks based on the maintenance trend and strategic importance. The procedure for estimating the failure rate and the probability calculation based on the Equation 5-4 is presented during the development of an excel template for risk analysis (Figure 5-8).

As the events are linked by 'OR' gates the probability of EPD is the addition of the four major logical gates. The design fault has been assumed as a constant probability of 1 in 10000 so its impact on the top event is low. The top event (EPD) probability of the road section is 7.39, which indicates that the road section may have approximately 7 to 8 early pavement damages within the next five years based on the failure rate of the root causes. In addition, a Microsoft Excel template was developed to calculate the probability of Permanent Pavement Damage (PPD) risk of a road section. A screenshot of the template is presented in Figure 5-8.

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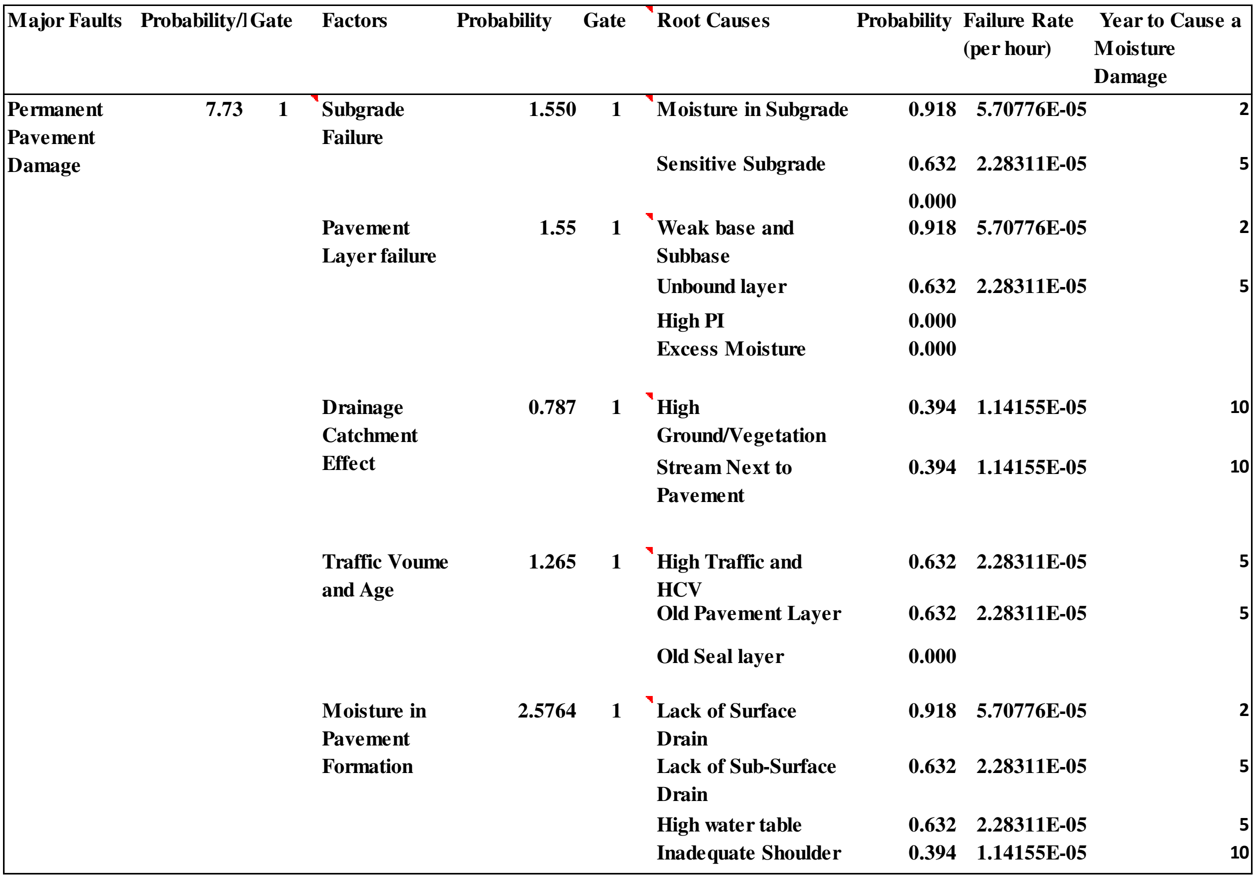
http://www.fault-tree-analysis-software.com/fault-tree-analysis

Table 5-2 Major Events and Root Causes of the Fault Tree for EPD

Code	Description	Type/Logical Gate	Probability(P) /Failure Rate (λ*)	Estimated No. of Years to Cause a Moisture Damage (Y)
EPD	Early Pavement Damage	OR	P=7.39E+00	
Bond Failure	Loss of bond between aggregate and binder	OR	P=2.94E+00	
Excess Moisture		OR	P=2.62E+00	
Shoulder and Edge Break		OR	P=1.84E+00	
Design Fault		Evident	P=1E-05	
Inadequate Shoulder		Evident	λ=5.7E-05	2
Wet Shoulder		Evident	λ=5.7E-05	2
Lack of Drainage		Evident	λ=1.14E-04	10
High Water Table		Evident	λ=1.14E-04	10
Complex Geo and Pavement		Evident	λ=2.28E-05	5
Low quality aggregate		Evident	λ=1.14E-04	10
Aged/Recycled Pavement		Evident	λ=2.28E-04	5
Wet Pavement		Evident	λ= 5.7E-05	2
High PI		Evident	λ= 1.14E-05	10

* Failure Rate λ= [1/(Y*365*24)]



Major Faults	Probability/I	Gate	Factors	Probability	Gate	Root Causes	Probability	Failure Rate (per hour)	Year to Cause a Moisture Damage
Permanent Pavement Damage	7.73	1	Subgrade Failure	1.550	1	Moisture in Subgrade	0.918	5.70776E-05	2
						Sensitive Subgrade	0.632	2.28311E-05	5
							0.000		
			Pavement Layer failure	1.55	1	Weak base and Subbase	0.918	5.70776E-05	2
						Unbound layer	0.632	2.28311E-05	5
						High PI	0.000		
						Excess Moisture	0.000		
			Drainage Catchment Effect	0.787	1	High Ground/Vegetation	0.394	1.14155E-05	10
						Stream Next to Pavement	0.394	1.14155E-05	10
			Traffic Voume and Age	1.265	1	High Traffic and HCV	0.632	2.28311E-05	5
						Old Pavement Layer	0.632	2.28311E-05	5
						Old Seal layer	0.000		
			Moisture in Pavement Formation	2.5764	1	Lack of Surface Drain	0.918	5.70776E-05	2
						Lack of Sub-Surface Drain	0.632	2.28311E-05	5
						High water table	0.632	2.28311E-05	5
						Inadequate Shoulder	0.394	1.14155E-05	10

Figure 5-8 Screenshot of the Template to Calculate Probability of PPD

Referring to Figure 5-8, the top event (Permanent Pavement Damage) is linked with the intermediate major factors by an ‘OR’ gate. The number ‘1’ is assigned to the ‘OR’ gate which indicates that the top event probability will be the sum of the probabilities of the root events. The number ‘2’ is assigned to the ‘AND’ logical gate which yields the top events’ probability as the product of the root event’s probabilities. Here the ‘IF Logic’ based formula is set up to work out the probability based on the logic gate (AND/OR) as seen in Figure 5-8. The root causes were identified through visual inspection, sub-surface investigation (coring) and from road asset management databases. Experts were requested to comment possible failure rate per hour due to the root causes. As seen in column 10 in Figure 5-8, some of the root causes can cause damage within 2 years or some may have delayed effect on road pavements (10 years). Here the moisture damage has been considered a failure in road pavements that require at least the stabilisation patches to repair. The failure rate per hour is calculated based on the estimation of failure. The probability of the root event is calculated based on the Equation 5-4 and the 5 year (43,800 hours) is used as the analysis period. The estimated probability of the permanent pavement damage (7.73) is obtained based on the estimation of the ‘OR’ logical gate. Therefore, the probability of the permanent pavement damage of the road section is the accumulation of the probabilities of the intermediate factors (Column 4). It also indicates that the road section may have approximately 7-8 moisture damage events (Failure) within the next five years. The template can be used to calculate the probability of both the EPD and PPD of any road section. Road controlling authorities could, for instance, set up a guideline that will specify the consequence or risk as ‘low’, ‘high’ and ‘ very high’ based on the probability of the early and permanent pavement damages on the road section.

5.6 Summary

This chapter assessed the application of the FTA technique in risk assessment for road sections. Fault trees are useful in manufacturing and process industries where a number of system and sub-systems are linked together to perform a desired function. The failure rate and their relation to the probability of failure are easily accessible in manufacturing and process industries. Although pavement asset management is seen as a process, it varies from the manufacturing process industries. The challenge was to build up the relationship between the failure and condition of the pavement or the causes of failure. Failure in a road pavement is slow compared to the comparatively drastic failure in manufacturing and process industries. As a consequence, the evolution of the risk analysis technique using FTA includes a number of assumptions that involves a considerable amount of expert opinion.

In spite of the challenges, the FTA based risk analysis technique was demonstrated in evaluating the moisture damage risk in road pavements. Moisture damage often develops at different stages and rates. In this respect, both the early development of moisture damage in road pavements along with the damages perennial in nature have been considered. Both the qualitative and quantitative approaches of FTA were demonstrated. The qualitative risk assessment can be indispensable to identify the potential causes of any premature failure in the road pavement. The quantitative risk assessment involves the development of a prediction method to identify the probability of failure both at early and end of life cycle of road pavements.

FTA can be used, particularly in the forensic investigation of road pavements, to identify the causes of the premature failure. Nevertheless, there is a considerable amount of expert judgment and assumption involved in the risk assessment process. Further research can be undertaken to reduce the amount of assumptions, and to improve the relationship between the failure probabilities and the failure rate. The quantification of root event probability can be correlated to the condition of the network. This will increase the reliability of FTA as a risk analysis technique in MDRA.

Chapter 6: Risk Assessment based on Combination of Moisture Damage Factors

6.1 Introduction

The MDRA framework includes a number of candidate risk analysis techniques. The incorporation of the fuzzy logic model and the FTA were presented in Chapter 4 and 5 respectively. This chapter presents the risk analysis technique of combining the distributions of the moisture damage factors. This risk analysis technique utilises experts' subjective judgment or rating of moisture damage factors based on the moisture damage parameters (Table 6-1). The output of the risk analysis technique is a combined distribution that can be used to predict the risk rating of a road section. The chapter also demonstrates the application of the technique for moisture damage risk assessment of a number of road sections.

6.2 Moisture Damage Risk Assessment (MDRA)

The MDRA was conceptualised to develop a risk assessment method to identify moisture damage potential in road pavements. The methodology to develop the MDRA as presented in Figure 6-1 was comprehensively described in Mia et al. (2013, 2014) and in Chapter 3.

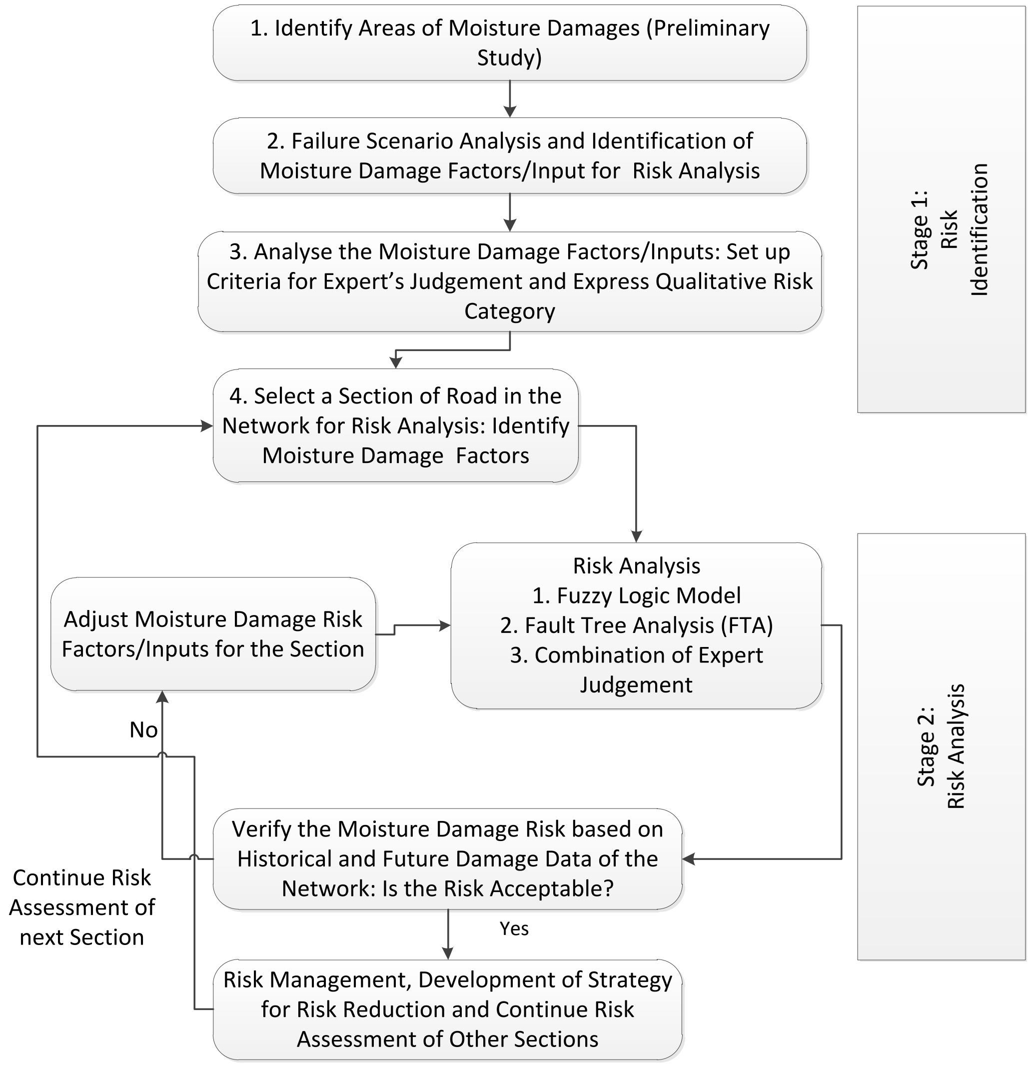


Figure 6-1 Framework of the MDRA

The two prime components of the MDRA are to identify the moisture damage factors and to utilise these factors to predict the risk of failure. The preliminary study to develop MDRA was helpful to identify the moisture damage factors. These moisture damage factors are processed through the risk analysis techniques to generate a risk rating of the road sections. These moisture damage risk ratings can be used for prioritising the road sections for drainage improvement. The moisture damage risk factors are presented in Table 6-1.

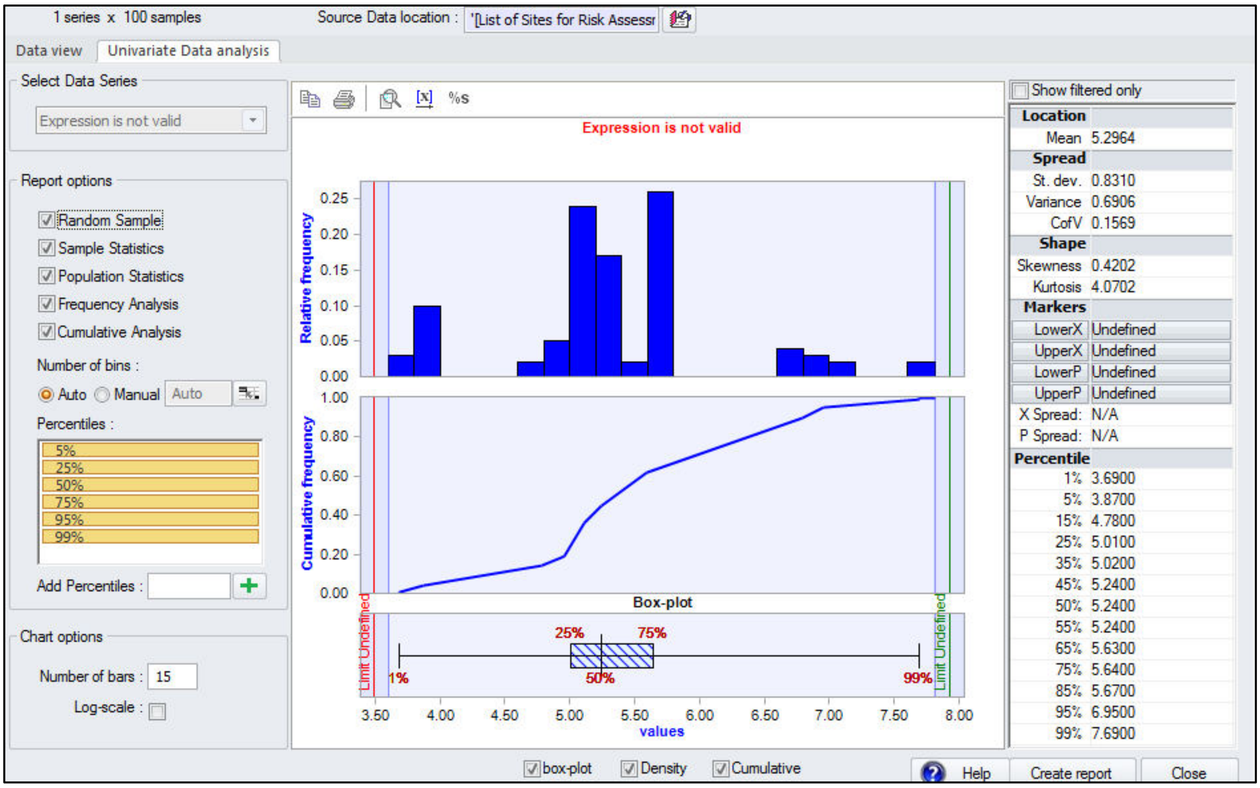
Table 6-1 Moisture Damage Factors Used in the Study

Category	Major Factors (Inputs)	Root cause/Parameter for evaluation
Static	G_Risk Geophysical and geometric features of the road pavement and drainage catchment (External to road pavement)	Side hill next to shoulder
		Stream within 10m
		Bush/Vegetation next to the shoulder
		High Stress/curve (Start-stop areas)
		Vertical Sag
	P_Risk Risk factors related to pavement profile	Topography (Flat, Rolling and Sloped terrain)
		Pavement construction (Cut and fill, Box cut)
		Sensitive subgrade
Dynamic	S_Risk Risk factors related to materials and the strength of the road pavement	Weak pavement layer
		Inadequate surfacing
		Old pavement and surfacing
		Materials with high PI/fines
	DRN_Risk Risk factors associated with drainage (surface and subsurface), traffic, climate, and shoulder (Within the road pavement)	Cross fall (inadequate)
		Kerb and channel blocked, damaged
		Subsoil drain non-functional
		Rainfall high
		Water table high (1 m from ground)
		Traffic volume high
		Heavy Commercial vehicle high
		Inadequate Shoulder

6.3 Methodology

This section describes the methodology used to develop a simulation based risk analysis technique for moisture damage risk assessment of road sections. The road sections were physically inspected or surveyed by video to identify the presence of moisture damage factors. Then expert evaluations were incorporated to assign a rating to each of the factors. The moisture damage risk factors (rating) were processed through a simulation model to develop the combined distribution that can be used to predict the Moisture Damage (MD) risk rating of the road section.

There are two distinct phases of the study. In phase 1, each road section was either inspected physically or surveyed through the video recording. The inspection should be conducted by experts who have the required experience of road network inspection to identify the pavement distresses. This form of road network inspection are predominant in major road maintenance contracts, especially the performance specified and network outcomes contracts. Usually the contract specification describes the criteria and suitable methods of inspection to identify the performance of the pavement, drainage measures and other features in the road network (Daly, 2004; NZTA, 2014). There are four major categories (geophysical, pavement profile, pavement material-strength and drainage) of moisture damage factors of the road section and each were rated on a scale of 1 to 10. This evaluation method was used to undertake a risk analysis based on the fuzzy logic model as presented in Mia et al. (2015) and in Chapter 4. During the second phase, a Microsoft excel add-in based simulation programme was used to develop the distributions of the risk factors of a road section. Figure 6-2 shows an example distribution (output) of a univariate set of rating (MD_Risk) processed through the data viewer tool of the simulation programme.


1 series x 100 samples

Source Data location : '[List of Sites for Risk Assessr

Select Data Series: Expression is not valid

Report options

☑ Random Sample
☑ Sample Statistics
☑ Population Statistics
☑ Frequency Analysis
☑ Cumulative Analysis

Number of bins : ● Auto ○ Manual Auto

Percentiles : 5% 25% 50% 75% 95% 99%

Add Percentiles :

Chart options

Number of bars : 15

Log-scale : ☐

Expression is not valid

☑ box-plot ☑ Density ☑ Cumulative

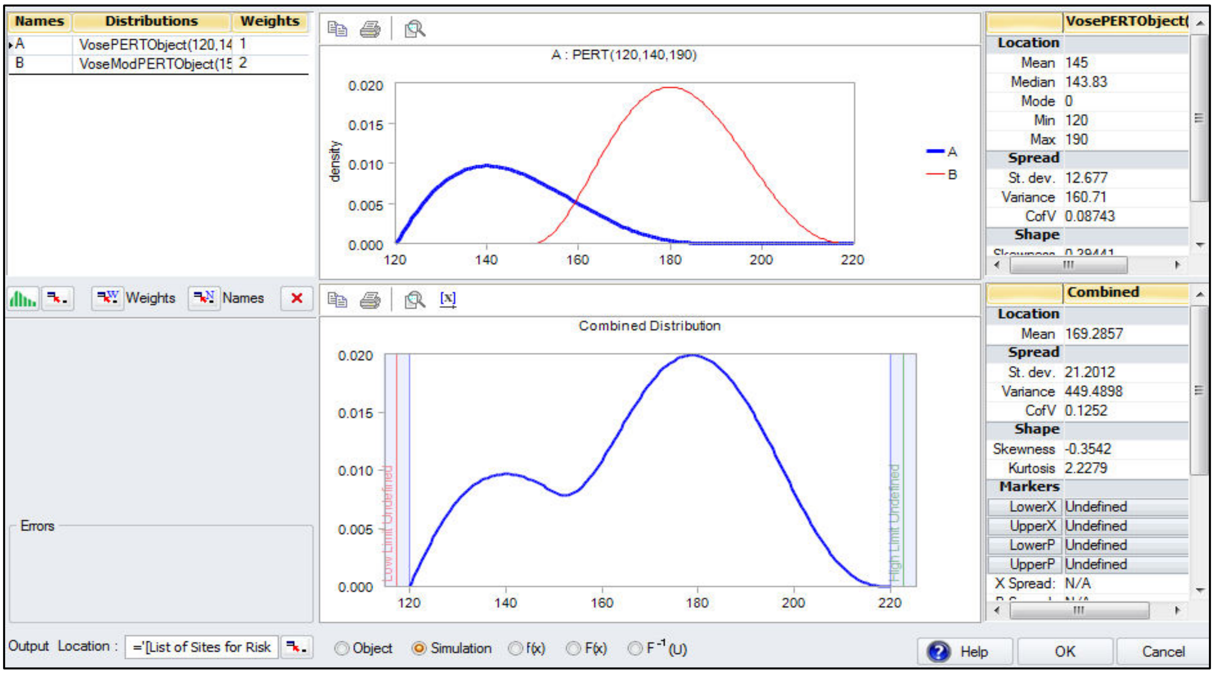
☐ Show filtered only

Location	
Mean	5.2964
Spread	
St. dev.	0.8310
Variance	0.6906
CofV	0.1569
Shape	
Skewness	0.4202
Kurtosis	4.0702
Markers	
LowerX	Undefined
UpperX	Undefined
LowerP	Undefined
UpperP	Undefined
X Spread:	N/A
P Spread:	N/A
Percentile	
1%	3.6900
5%	3.8700
15%	4.7800
25%	5.0100
35%	5.0200
45%	5.2400
50%	5.2400
55%	5.2400
65%	5.6300
75%	5.6400
85%	5.6700
95%	6.9500
99%	7.6900

Figure 6-2 Distribution of MD_Risk of 100 Road Sections Using Data Viewer

The top box shows the relative frequency of the risk ratings. The majority of the data is within a risk rating of 4 to 6. The mean (5.294), standard deviation (0.8310), variance (0.6906) and the coefficient of variation (0.1569) values can be used to develop a representative distribution of the risk rating data. In addition, the skewness and kurtosis values can be used to refine the shape of the distribution curve. This indicates that the data viewer tool can be effectively utilised to develop a distribution of any set of data (rating) based on expert judgement.

The next step was to develop a single distribution through a combination of distributions of different moisture damage factors. The resultant distribution is supposed to reflect the combined effect of the moisture damage factors. Here, four different distributions of moisture damage factors were simulated to yield a distribution that was used to predict the risk rating of the road section. The distributions were aggregated based on the theory of superposition and in this case the ‘Aggregate Distribution’ module of the Model Risk (Figure 6-4) programme is used to develop the resultant distribution. In Figure 6-3, two distributions (A & B) are aggregated to yield the combined distribution in the box below. The horizontal axes of the distributions are the values or ratings assigned by the experts based on the moisture damage parameters in Table 6-1. The vertical axis is the relative density of the assigned ratings (in the scale of 1 to 10). The input distributions can be weighed differently based on their effect on the combined distribution or on the severity of risk. The names, weights and the distributions can be selected from an excel sheet or they can be manually entered into the left hand top corner of the module. The subjective PERT distributions were used for the moisture damage factors that were combined based on the principle of superposition. The input distribution can be modified by changing the parameters (Minimum, maximum, mode, mean, and median) in the box on the left hand side of the module (Figure 6-3).



Names	Distributions	Weights
A	VosePERTObject(120,14	1
B	VoseModPERTObject(15	2

	VosePERTObject(
Location	
Mean	145
Median	143.83
Mode	0
Min	120
Max	190
Spread	
St. dev.	12.677
Variance	160.71
CofV	0.08743
Shape	

	Combined
Location	
Mean	169.2857
Spread	
St. dev.	21.2012
Variance	449.4898
CofV	0.1252
Shape	
Skewness	-0.3542
Kurtosis	2.2279
Markers	
LowerX	Undefined
UpperX	Undefined
LowerP	Undefined
UpperP	Undefined
X Spread:	N/A

Output Location : ='[List of Sites for Risk

○ Object ● Simulation ○ f(x) ○ F(x) ○ F^{-1}(U)

Figure 6-3 Screenshot of Combined Distribution Model Used in this Study

The combined distribution in Figure 6-3 represents the risk rating of the treatment length or site. The specified risk rating can then be extracted based on the specified percentile rating of the combined distribution curve.

Finally, a number of road sections selected in the network were used for risk analysis using the combined distribution method. These sites were selected from the treatment sections selected for rehabilitation from the year 2010 to 2013. Usually the rehabilitation sites are selected based on the output of the deterioration modelling (Henning et al., 2006) used for road network maintenance need. The deterioration model usually identifies the most vulnerable sites that are prone to failure and need immediate attention through rehabilitation or major repair work. In addition, these sites were scrutinised for moisture damage risk through the fuzzy logic model. Therefore, the reassessment of these road sections using the simulation method will help in correlating the output of the study with the deterioration modelling and fuzzy logic model used as other candidate risk analysis techniques in this research.

6.4 Results and Discussion

The road network is usually divided into a number of sub-networks based on their highway classification, importance and traffic volume. Each sub-network is composed of a number of sections of a State Highway in New Zealand. Each State Highway of a network is subdivided into a number of treatment lengths, usually between 0.5 and 1.0 km in length. The pavement age and surface of the road sections of a treatment length used to be homogenous. However, the routine maintenance of different sections may vary within the treatment length because of differences in pavement distress and failure pattern. The differences in pavement distress of the road section within a treatment length are mostly because of the moisture damage factors identified during the study. Based on this, any treatment length or site selected for this study was subdivided into 100 m road section. The 100 m road sections are easy to survey for performance and have been adopted by the New Zealand Transport Agency for its prioritization process in the road network maintenance (NZTA, 2014). The ratings of the 100 m road sections of a treatment length can generate distribution curves of the moisture damage factors. These distribution curves of moisture damage factors were combined to develop a distribution that represents the moisture damage risk of the treatment length.

6.5 Incorporation of Expert Opinion

Expert opinion is vital in road asset management. Often, the road network generates an excess demand for maintenance work compared to the actual funding available. Therefore, it requires extensive prioritisation to manage the road network within the limited resources. In addition, road network performance assessment is also crucial, especially in the recent network outcomes contract. This requires frequent inspection and monitoring of road networks for pavement distresses like rutting, roughness, flushing, cracking and texture deficiency. Though a number of high speed and automated testing or survey facilities are used, expert physical inspections are warranted to ensure comprehensiveness of the prioritisation process. The forensic investigation to detect the cause of premature failure in road pavements also involves extensive site inspections as well as both destructive and non-destructive tests (Chen et al, 2006; Chen, 2007). All of these processes in road network maintenance include the direct or indirect involvement of expert judgement.

There is a difference of inclusion of expert judgment in the two risk analysis techniques used so far. In the fuzzy logic model, expert judgment was incorporated to identify the risk rating of the 100 m road section of a treatment length (Mia et al., 2015). Whereas, this combined distribution model amalgamates the expert for each 100 m road section to yield the combined risk rating for the treatment length. Therefore, these two risk analysis techniques can be complementary to identify both the risk rating of a 100 m road section and the combined rating of the treatment length.

6.5.1 Case Study

In order to demonstrate the combined distribution risk analysis method one rehabilitation site was chosen. The site is one of the most complex road sections on the network. The length of the site is 1 km, so 10 road sections of 100 m were selected for the study. Most of the road sections in the site involve complex geography with a side hill, large stream and high vegetation at the shoulder. A number of the road sections are on high stress horizontal curves along with vertical sag curves due to changes in grade at different sites. The road pavements are mostly cut and fill, and lack sufficient cross fall at different locations. The site had a history of flooding and the ground water table is relatively shallow. The shoulders in the road sections were mostly unsealed and inadequate due to geographical restrictions. The drainage was improved during the last rehabilitation and subsoil pipes were installed in most of the road sections next to the side hill to reduce the intrusion of water into the pavement formation (SADC, 2003). The site was last rehabilitated in 2011, and since then most of the road sections have shown signs of pavement distresses such as rutting, flushing, pumping, scabbing and potholes. The maintenance costs of the road section are increasing over time due to the number of stabilisation patches done in last three years.

The site has been monitored since 2011. Both wet and dry season inspections were carried out for the study. The risk analyses of the road sections were conducted both at pre and post-rehabilitation (2014). Pre-rehabilitation site photos, test pit, and FWD test data were considered to evaluate the risk rating of the moisture damage factors. Though the static (G_Risk and P_Risk) factors remain the same over the monitoring period, however, the dynamic factors (S_Risk and DRN_Risk) change due to the rehabilitation of pavement and drainage improvement of the site. The current trends of pavement distresses and failure were also considered during the evaluation of pavement strength and drainage performances.

Table 6-2 contains the risk rating of the moisture damage factors of the 100 m road sections in the site. The risk ratings of both the pre and post rehabilitation have been tabulated. The risk rating is made based on the evaluation of the road sections through the chart in Table 6-1. The higher the triggers generate based on the chart, the higher will be the risk rating. Usually the number of triggers will reflect the category (Low, Moderate and High) of the risk; however, an expert judgment can be used to finalise the risk rating of the moisture damage factors (in the scale of 1 to 10).

Table 6-2 Moisture Damage Factors Risk Rating (Scale 1: Low to 10: Very High)

Road Section	G_Risk (Pre)	G_Risk (Post)	P_Risk (Pre)	P_Risk (Post)	S_Risk (Pre)	S_Risk (Post)	DRN_Risk (Pre)	DRN_Risk (Post)
A	8	8	9	6	9	5	9	5
B	8	8	9	6	9	5	9	5
C	7	7	8	6	8	6	7	6
D	6	6	7	4	8	4	8	5
E	9	8	9	7	9	5	9	7
F	9	9	9	8	8	4	9	6
G	9	8	9	6	9	6	8	4
H	6	5	7	4	9	6	8	5
I	7	7	8	6	8	5	9	5
J	9	7	8	6	6	4	7	4

The risk ratings (Table 6-2) of the moisture damage factors are processed through the data viewer module. Figure 6-4 and Table 6-3 show the distribution of the moisture damage factors in order to combine them for the resultant distribution.

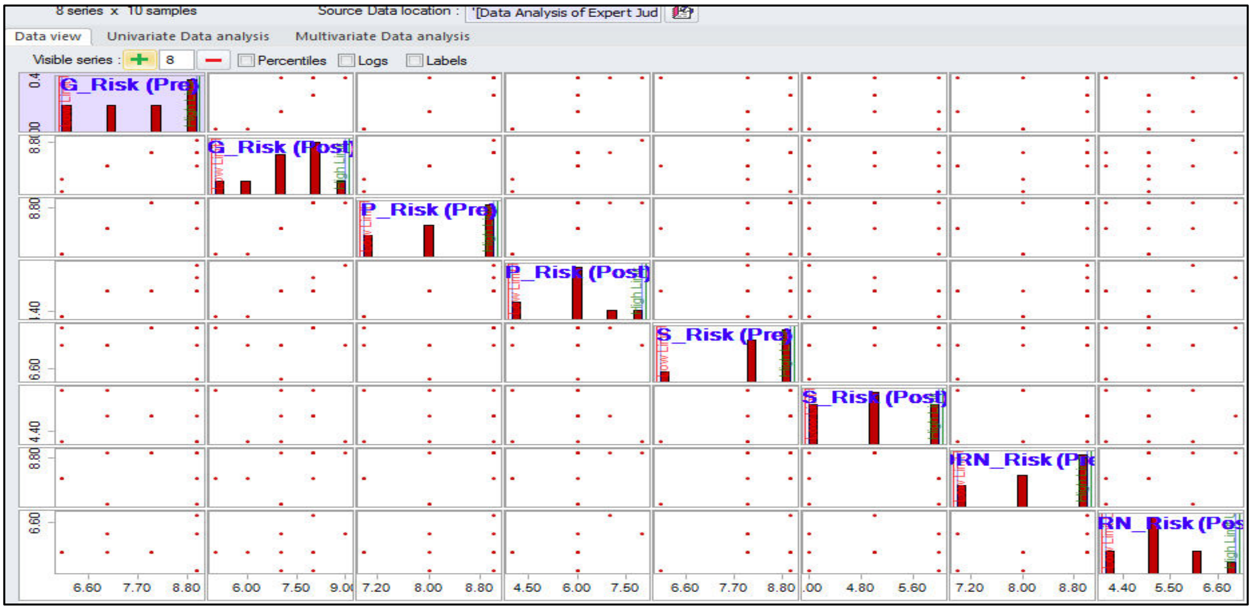


Figure 6-4 Multivariate Distribution of Moisture Damage Factors of the Site

Figure 6-4 shows the multivariate distribution of moisture damage factors. These are the input distributions for the risk analysis. There are two distributions for each of the factors, denoting the pre and post-rehabilitation of the road sections. The risk ratings are on the horizontal and the frequencies of the rating (in fraction) are on the vertical axis of the distributions. This distribution can be linked to any excel sheet and any changes in that sheet will change the distribution also. The change in distributions of any factor in pre and post is due to the changes in pavement profile, strength and drainage due to the rehabilitation of the site.

Table 6-3 Output of the Data Processing/ Input Distribution for Risk Analysis

	G_RISK (PRE)	G_RISK (POST)	P_RISK (PRE)	P_RISK (POST)	S_RISK (PRE)	S_RISK (POST)	DRN_RISK (PRE)	DRN_RISK (POST)
MINIMUM	6.00	5.00	7.00	4.00	6.00	4.00	7.00	4.00
MAXIMUM	9.00	9.00	9.00	8.00	9.00	6.00	9.00	7.00
MEAN	7.80	7.30	8.30	5.90	8.30	5.00	8.30	5.20
STANDARD DEVIATION	1.23	1.16	0.82	1.20	0.95	0.82	0.82	0.92
VARIANCE	1.51	1.34	0.68	1.43	0.90	0.67	0.68	0.84
COFV	0.16	0.16	0.10	0.20	0.11	0.16	0.10	0.18
SKEWNESS	-0.43	-0.73	-0.69	-0.25	-1.72	0.00	-0.69	0.60
KURTOSIS	1.54	3.51	1.96	3.65	6.53	1.61	1.96	3.40

The output of the Data Viewer module (Table 6-3) has been used to develop the input distributions that will be combined through the simulation model. In most of the distributions, the minimum, maximum, mean and mode values of any set of data need to be entered. Here, the PERT distribution was used as the input for the simulation. Figure 6-5 shows the four input distributions (moisture damage factors) and the combined distribution in two boxes.

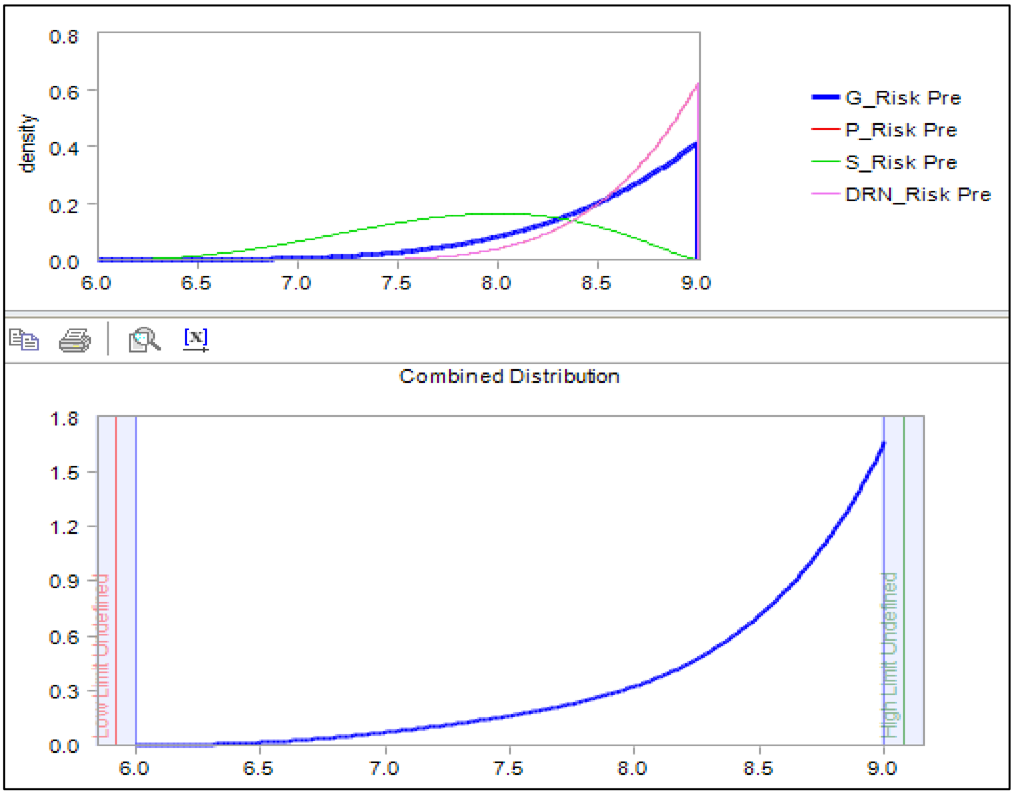


Figure 6-5 Simulation of Moisture Damage Factors (Pre-Rehabilitation)

The combined distribution in Figure 6-5 (bottom box) represents the amalgamated moisture damage risk of the whole treatment length before the rehabilitation. The horizontal axis denotes the risk rating and the vertical axis shows the frequency or density of the ratings. In this case, the moisture damage factors have been considered to carry equal weights. The weighting of the factors can be adjusted easily, so site specific weights can be applied in this risk analysis technique. Figure 6-6 gives the combined distribution model of the moisture damage factors after the rehabilitation programme.

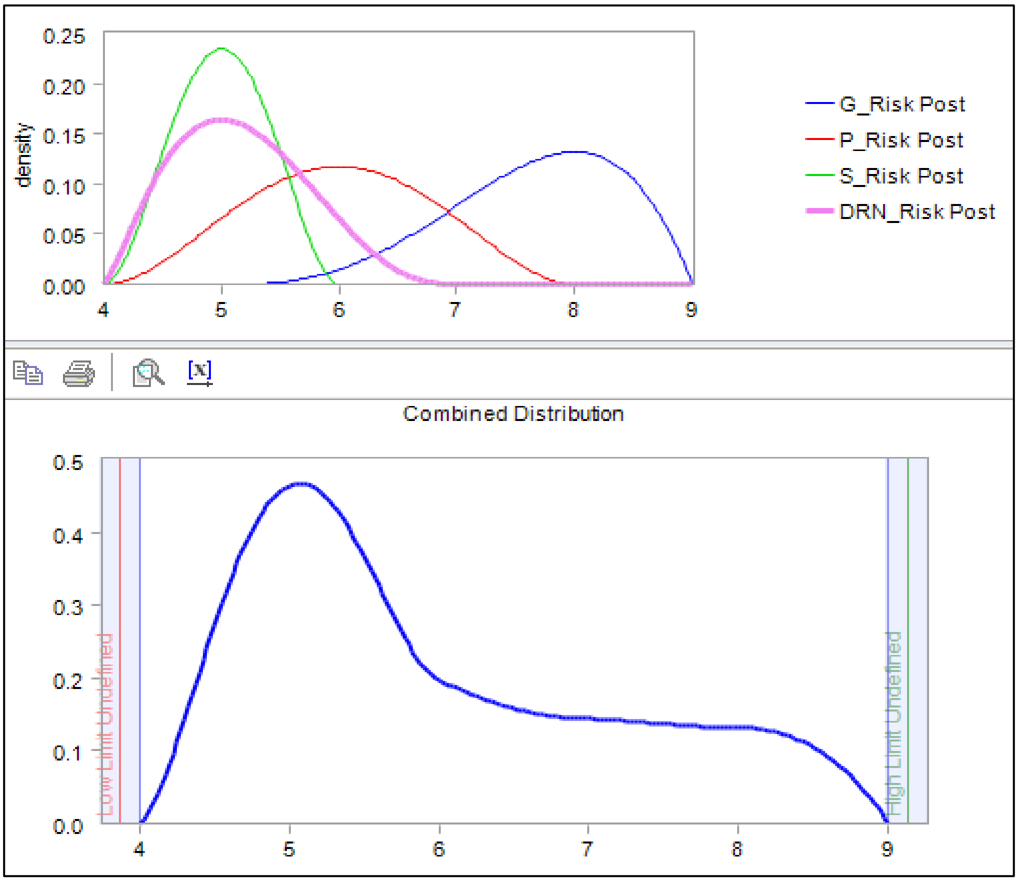
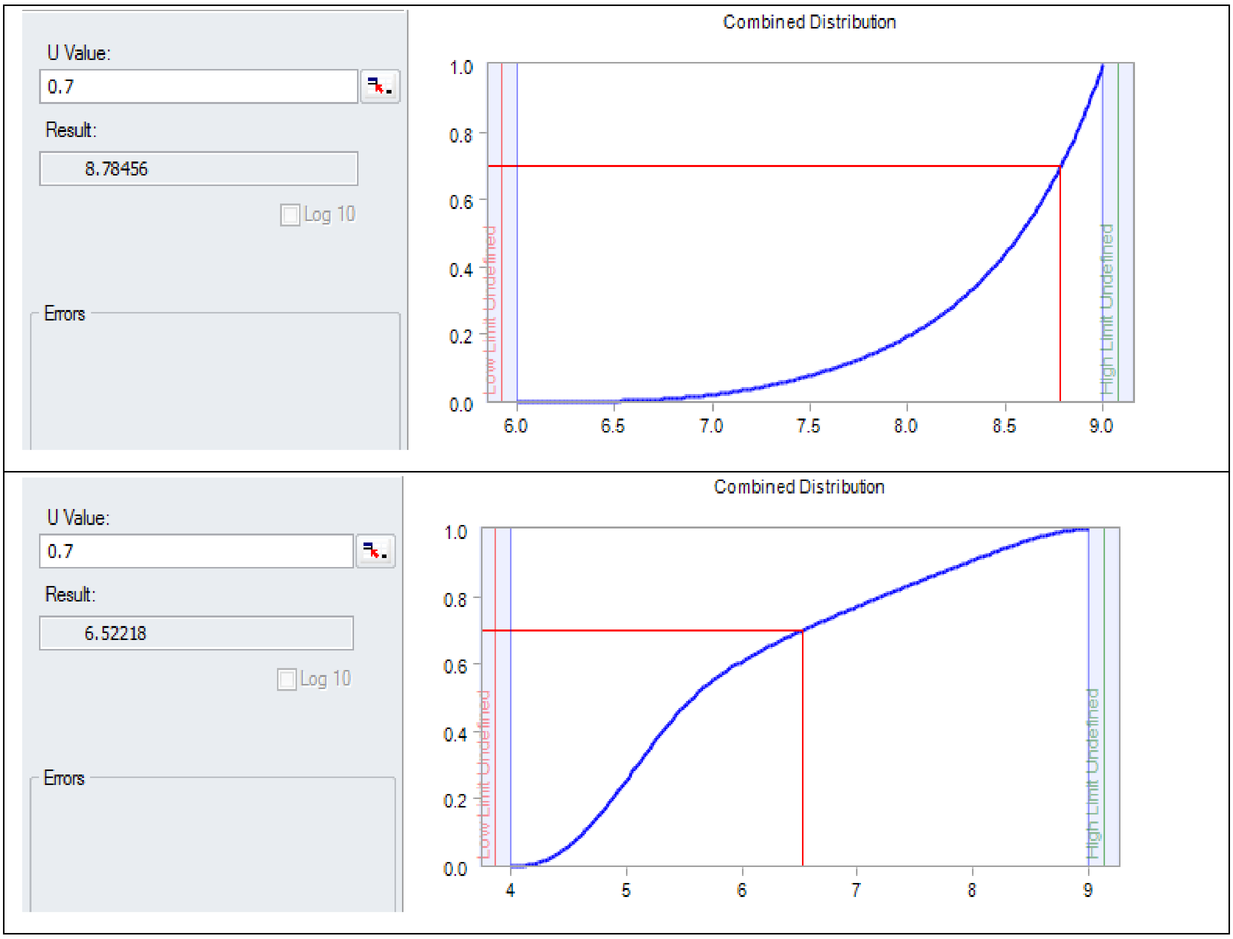


Figure 6-6 Simulation of Moisture Damage Factors (Post-Rehabilitation)

The strength (S_Risk) and drainage (DRN_Risk) factor's rating improved slightly and as a result changed the input and the combined distribution model. The combined distribution model was used to develop a risk rating for the treatment length. In this case, the 70thpercentile risk rating of the combined distribution (cumulative) is assumed as the representative risk rating of the treatment length (Figure 6-7). Here two risk ratings, 8.78 and 6.52, are obtained from the two pre and post rehabilitation combined distributions. Any percentile (in fraction) value entered into the U value box (Figure 6-7) will give the risk rating from the combined distribution curves (cumulative).


U Value: 0.7

Result: 8.78456

☐ Log 10

Errors

U Value: 0.7

Result: 6.52218

☐ Log 10

Errors

Figure 6-7 Combined Risk Rating (Post and Pre Rehabilitation)

The combined risk rating can be expressed as a range from the 50th to the 90th percentile of the density value (vertical axis of Figure 6-7). The higher the risk rating of a road section indicates the higher the probability of premature failure especially from moisture damage.

6.6 Summary

In this chapter, the incorporation of expert judgment is demonstrated for moisture damage risk assessment of road sections. Although there is involvement of expert judgement in risk assessment, the evaluation of the moisture damage factors of the site is mostly guided by the trigger-based parameters in Table 6-1. The risk analysis technique can be replicated or used for any road section through the demonstrated methodology in the case study. The Model Risk add-in for Microsoft Excel has been utilised to develop the risk analysis technique. Due to the subjective characteristics of the moisture damage factors in the study, the risk analysis was conducted using the ‘Aggregate-Distribution’ tool of the programme. The risk analysis technique is particularly suitable to identify the combined risk rating of a treatment length/site based on the moisture damage factors of subdivided (100 m) road sections. The next chapter demonstrates the comparative study of the three candidate risk analysis techniques in the study.

Chapter 7: Comparative Analysis of the Risk Analysis Techniques

7.1 Introduction

This chapter presents a comparative study of the candidate risk analysis techniques. The candidate risk analysis techniques in this study were described in the previous chapters of the thesis. The rationale for initially selecting the candidate risk analysis techniques was presented in Section 2.6 of the literature review (Chapter 2). The risk analysis techniques were successfully utilised in the moisture damage risk assessment, however, further study on evaluation of their performance and other intrinsic features will assist in identifying the optimum technique for the MDRA.

7.2 Risk Analysis Techniques

The risk analysis techniques in this study are key components of the MDRA. The development and application of the fuzzy logic model, FTA and the 'combination of moisture damage factors' in the MDRA were demonstrated in the previous three chapters. The MDRA required the development of a comprehensive moisture damage parameter table (Table 4-5) to identify the extent of the moisture damage factors. Once the parameters were tabulated, expert judgement was involved in defining the moisture damage factors or inputs for the risk analysis techniques. Thus the first two steps are common in the MDRA for all three techniques, albeit with some minor variations. However, there are differences in performance, output, methodology, implementation time, applicability, assumptions and limitations of the three techniques used in the study. Therefore, the risk analysis techniques are investigated thoroughly to identify the optimum technique for the MDRA.

A. Fuzzy Logic Model

The Fuzzy Inference System (FIS) editor toolbox in the Matlab programme was used in this study as one of the candidate risk analysis techniques. This fuzzy logic model has been effectively utilised in different sectors or disciplines for risk analysis (Rezakhani, 2012;

Zlateva et al., 2011). The risk analysis technique incorporates the linguistic expression of risks (Low, High and Very High) by the experts and generates the output of the risk analysis based on a number of inference rules. The output of the risk analysis is the rating of risk on a scale. The linguistic expression of the risk needs to be assigned a membership function (trapezoidal or triangular). The 'IF-Then' based inference rules are developed based on the network performance and expert judgement. The inference rules have to be entered into the model and can be edited at any time. There is scope to assign differential weights for the inputs of the risk analysis. The outputs of the risk analysis are also linguistic expressions such as low, high, very high and each of them is assigned with a membership function as well. During analysis, the output is derived as a rating (on a scale) which is "defuzzified" to linguistically express the moisture damage risk of a road section.

B. Fault Tree Analysis (FTA)

The FTA technique used in this study is primarily developed based on literature review and expert judgement. Two distinctive fault trees were developed to identify the risk of moisture damage at an early stage (within 5 to 7 years) or permanent damage at the end of the life cycle of a road pavement. The fault tree for early pavement damage can be used for road a section that was rehabilitated within the last five to seven years and is to identify the risk of premature failure. The fault tree for the permanent pavement damage is used to assess the road sections and to identify the hot spots for drainage in a road network. These hot spots are critical in the road network and implementation of proactive drainage in those spots can reduce the risk of failure. In addition, the output of the risk analysis can justify the proposed drainage improvement in a road network along with the preservation activities (pavement renewal and resurfacing) in the road network. The FTA is conducted to assess the road section both qualitatively and quantitatively. The qualitative FTA analysis uses the fault trees to demonstrate the critical paths of failure for any particular road section. Once the failure paths are identified, remedial measures can be proposed to reduce the extent of the moisture damage factors. The quantitative FTA is implemented to identify the probability or likelihood of the failure in percentage or number. In Chapter 5, both the FTA techniques based on qualitative and quantitative analysis were demonstrated.

C. Combination of Moisture Damage Factors (Distribution)

This risk analysis technique involves the combination of the distributions of moisture damage factors. In this study the 'Model Risk' add-in for Microsoft excel was used to develop the risk analysis technique. It is particularly applicable to the development of the combined risk rating of a road section or a treatment length. A treatment length can be a multiple 100 m road section so the unit for risk assessment in this research. Once the road sections are assessed for the moisture damage parameters, the risk rating (on a scale) of the input moisture damage factors is defined based on expert judgement. For a treatment length, each of the moisture damage factors may have a range of values for the multiple 100 m road sections. These values are processed to generate the distribution for each of the moisture damage factors. These distributions are then aggregated by the Model risk programme to generate the resultant curve that represents the combined risk rating for the treatment.

7.3 Comparative Study of the Risk Analysis Techniques

The objective of the comparative study is to assess the performance (strength) of the risk analysis techniques in identifying the appropriate risk level of each road section. The moisture damage risk rating identified through the risk analysis can be used for prioritising the road sections for drainage improvement. This comparative study involves the comparison of the technical aspects of the risk analysis techniques. The speed, reliability, effectiveness and efficiency of the risk analysis techniques depend on technical competencies. In addition, the comparative study involves a number of features related to the practical implementation of the risk analysis techniques. The proactive implementation of the risk analysis techniques is crucial because the MDRA is designed to be applied in road network maintenance. Therefore, the availability and effectiveness of the techniques in risk assessment have to be scrutinised during the comparative study.

7.3.1 Methodology of the Comparative Analysis

The comparative study of the risk analysis techniques is demonstrated in Figure 7-1. This was conducted in the following phases;

- One major challenge was to identify the appropriate performance indicators for the risk analysis techniques. An in-depth knowledge of the techniques and the common goal of measuring the accuracy of the predicted risk, helped in developing a platform to summarise the existing literature.
- The next input in the process is representative road sections that were used to assess the performance of the risk analysis techniques. The criteria for selection of the road sections is presented later in Section 7.4.2.

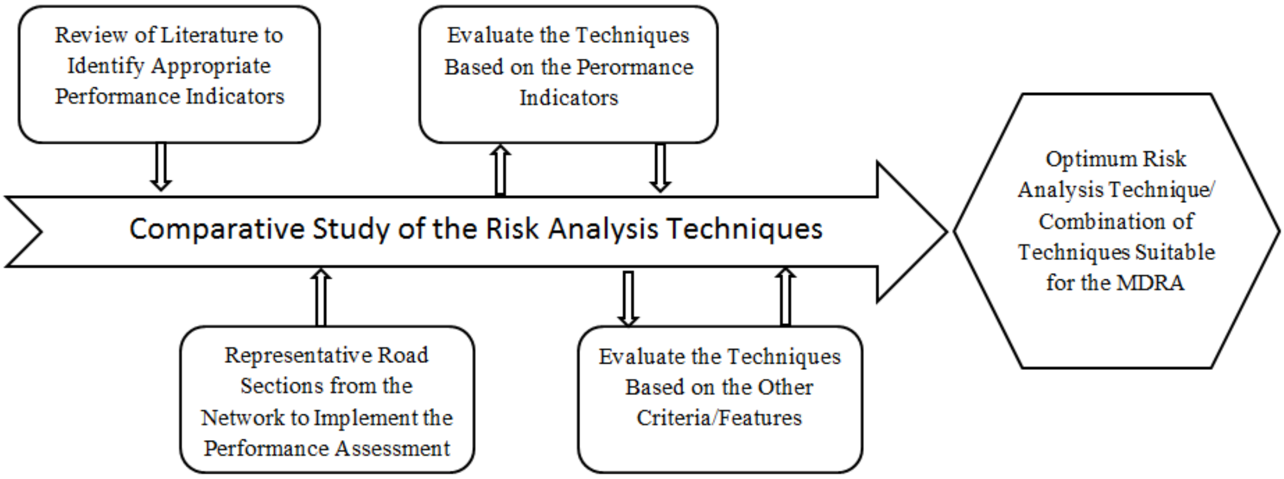


Figure 7-1 Comparison of the Risk Analysis Techniques (Process)

- The next step in assessing the risk analysis techniques is to evaluate them using appropriate performance indicators. The evaluation process will help in better understanding of the techniques and eventually provide a ranking of the risk analysis techniques based on their performance.
- Lastly, the risk analysis techniques are evaluated based on the practicality criteria such as the implementation time, availability, transferability, limitations and applicability to drainage needs assessment. This is to ensure that an effective and efficient evaluation of the techniques in order to fulfil the objective of the research.

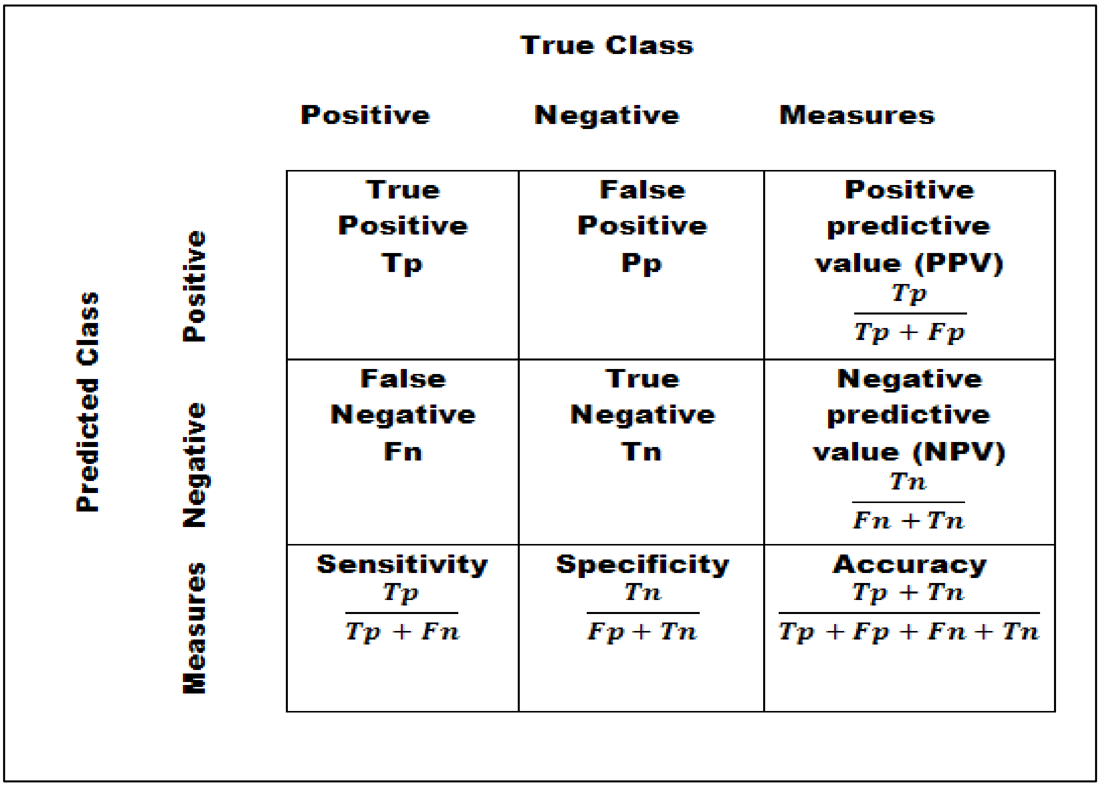
Overall, the comparative study is to identify an optimum risk analysis technique or a combination of techniques that will be effective for assessing the road sections with greater certainty.

7.4 Performance Measurement of the Risk Analysis Techniques

The performance measurement in risk analysis is expected to be fairly simple, often designated by the success in predicting the undesired event or risk. However, it was a challenge to identify appropriate performance measurement indicators for the risk analysis techniques used in this study. In traditional risk assessment, the performance of a technique involves the success in predicting the probability and consequence of undesired events such as natural disasters (Zlateva et al., 2011), and financial loss due to disruption of production and construction (Carr & Tah, 2001). The assessment of performance of these risk analysis involves a comprehensive review of the historical database of previous events and their causes of failure. The objective of risk assessment in this study varies considerably from the concept of traditional risk management. The target is to set up a rating-based risk prediction method that can be used to prioritise the drainage needs of the road network. The road controlling authorities rarely account for the risk of failure due to factors like geography, climate, traffic and excess moisture in road pavements. They are historically focused on catastrophic events such as slip failure, rock fall and flooding. Therefore, the assessment of performance of the risk analysis techniques through the traditional risk management concept was not feasible. Rather, it was essential to identify an indirect approach for performance assessment of the risk analysis techniques.

Performance assessment is an important aspect of the evaluation of various classification techniques used for software development and risk analysis. The classification techniques are evaluated based on their capability in predicting or classifying the desired output from large databases. Among them binary classifiers are machine based techniques used to identify or classify either 1 or 0 from a large database. The binary objects (1, 0) are used to represent a number of logical arguments such as ‘Yes/No’, ‘True/False’. For example, Vihinen (2012) used two states (Positive/Negative) binary classifiers in predicting the effect of genetic variations on DNA (Dioxy Ribonucleic Acid), RNA (Ribonucleic Acid) and protein level. Several prediction tools were trialled and the evaluation of their performance was crucial.

Figure 7-2 shows the contingency matrix developed and used for evaluation of the classification techniques and the prediction tools. The number of correctly predicted specimens from a database is denoted by ‘True Positive (TP)’ whereas; the number of falsely predicted specimens is the ‘True Negative (TN)’ of the contingency matrix. On the other hand, any negative specimen predicted as positive is ‘False Positive’ and the positive samples predicted as negative are in the group of ‘False Negative’. Both the ‘False Positive’ and ‘False Negative’ are undesirable and reduce the accuracy of the prediction tools. The sensitivity, specificity, positive predicted value, negative predicted value and accuracy (Figure 7-2) were used as the performance indicators during the evaluation of the prediction tools (Vihinen, 2012).



		True Class		
		Positive	**Negative**	**Measures**
Predicted Class	**Positive**	**True Positive Tp**	**False Positive Pp**	**Positive predictive value (PPV)** $\frac{Tp}{Tp+Fp}$
	Negative	**False Negative Fn**	**True Negative Tn**	**Negative predictive value (NPV)** $\frac{Tn}{Fn+Tn}$
	Measures	**Sensitivity** $\frac{Tp}{Tp+Fn}$	**Specificity** $\frac{Tn}{Fp+Tn}$	**Accuracy** $\frac{Tp+Tn}{Tp+Fp+Fn+Tn}$

Figure 7-2 Contingency Matrix based Performance Indicators (Vihinen, 2012)

Comparison of risk analysis techniques was adopted in assessing the risk of software development (Elzamly & Hussin, 2014). A number of performance indicators were used to assess the accuracy of two new developed multiple regression analyses. The application of performance indicators such as ‘Mean Magnitude of Relative Error (MMRE)’ and ‘Pred (25)’ was effectively introduced to assess the accuracy of the regression tools in software development risk analysis. First of all, the Magnitude of Relative Error (MRE_i) is calculated for each regression technique using Equation 7-1.

$$MREi = \frac{[Actual\ Effort\ i - Predicted\ Effort\ i]}{Actual\ Effort\ \ i} \qquad \textbf{Equation 7-1}$$

The MMRE (Equation 7-2) is the average of the magnitudes of relative errors for a particular regression tool and is inversely proportional to the accuracy of the classification technique.

$$MMRE = \frac{1}{n}\sum_{i=1}^{i=n}\frac{[Ei-Et)}{Ei} \qquad \textbf{Equation 7-2}$$

Where E_i = Actual Error, Et = Prediction Error

n = Total number of observations

The MMRE is effectively used in comparing the accuracy of prediction models and it also provides a quantitative measure of the uncertainty of a prediction tool. In addition, Pred (25) (Equation 7-3) has been used as a performance indicator which is proportional to the accuracy of a technique.

$$\boldsymbol{Pred\ (25)} = \frac{\boldsymbol{k}}{\boldsymbol{N}} \quad \textbf{Equation 7-3}$$

Where, k= Number of observations with MRE less than or equal to 0.25

N= Total number of observations

Therefore, the Pred (25) states the percentage of predicted observations of MRE less than or equal to the value of 0.25. These two performance indicators were successfully demonstrated to compare the newly developed prediction tools (Elzamly & Hussin, 2014).

Classification techniques have been used in road asset management for detecting the reasons for any pavement distress. Schlotjes et al. (2014) has successfully demonstrated the utilisation of several classification techniques in diagnosing the causes of pavement failure such as rutting, cracking and shear. One vital component of this study was to measure the performances of the classification techniques. Similar to the study of Vihinen (2012), they have used the concept of confusion matrix and relevant parameters (Sokolova & Lapalme, 2009) to rank the classification techniques based on their performance. Table 7-1 presents the confusion matrix and the associated parameters and equations used in their study (Schlotjes et al., 2014).

Table 7-1 Confusion Matrix and Relevant Performance Indicators

		Data Failures		
		0	**1**	
Predictions	0	True Positive (Tp)	False Positive (Fp)	(N_1)Number of Predicted non-Failures
	1	False Negative (Fn)	True Negative (Tn)	(N_2)Number of Predicted Failures
		(N_3)Number of Predicted non-Failures	(N_4)Number of Predicted Failures	(N_{Total}) Total number of Sites (or predictions)
Indicators used for Performance	Precision (p)	$p = \frac{Tp}{Tp + Fp}$		
	Recall (r)	$r = \frac{Tp}{Tp + Fn}$		
	Accuracy	$Accuracy = \frac{\sum(Tp + Tn)}{N\ Total} * 100\%$		

Measures	Misclassification Error	$Missclassification = \frac{\sum(Fp + Fn)}{N\ Total} * 100\%$
	F Score	$FScore = \frac{2 \times p \times r}{p + r}$
	Phi Coefficient (θ)	$\theta = \frac{(Tp \times Tn) - (Fp \times Fn)}{\sqrt{N1 \times N2 \times N3 \times N4}}$

(Sokolova & Lapalme, 2009; Schlotjes et al., 2014)

In order to evaluate the classification techniques, the performance indicators in Table 7-1 were used. The true positive (Tp) represents the correctly predicted sound pavements assigned in '0' class and the false negative (Fn) includes the sound pavements predicted to fail. The failed pavements were assigned in '1' class and true negative are correctly predicted failures, whereas, the false positive are failed sites incorrectly predicted as sound. Four performance indicators (accuracy, misclassification error, F-Score and phi-coefficient) were used to qualify the classification techniques. The accuracy and misclassification are relatively straightforward and measures the success and the relative error in predicting the condition of the pavements during the testing of the classification techniques. F-score is added to increase the comprehensiveness of the performance measurement and to reduce the tendency of bias through judgement of the classification techniques alone by accuracy and misclassification error. In addition the parameter phi-coefficient (Matthews Correlation Coefficient) was used to measure the agreement between the inputs and output of the classification techniques which essentially denotes the prediction of sound or failed pavements (Parker, 2011 as cited in Schlotjes et al., 2014). Overall the performance indicators were successfully demonstrated to distinguish the classification techniques that were used to predict the probability of failure due to rutting, cracking and shear in road pavements.

Similar to the classification techniques used in Vihinen (2012) and Schlotjes et al. (2014), the risk analysis techniques in this research are to predict the risk of failure in road pavements due to moisture damage. Although the output of the risk analysis techniques is not binary numbers, the basic question asked after the analysis is whether the road section is at risk of moisture damage (Yes/No)? Any road section predicted to be in the high or very high group can be considered as at risk, whereas the rest of the road sections are not at risk. Therefore, the performance evaluation methods and indicators adopted in the studies can be modified for use in this research to assess the performance of the risk analysis techniques.

7.4.1 Performance Measurement Indicators

Based on the above review of the assessment of classification techniques, a performance contingency matrix (Table 7-2) has been developed to evaluate the risk analysis techniques. The Performance Contingency Matrix used in this study includes the following groups of road sections;

A. **True High (Th):** These road sections are actually at risk of moisture damage and the risk analysis techniques have correctly predicted their risk rating;
B. **True Low (Tl):** These road sections are at low risk of moisture damage and the risk analysis techniques have correctly predicted their low risk rating;
C. **False High (Fh):** These road sections are low risk and the risk analysis techniques have incorrectly predicted them at high risk;
D. **False Low (Fl):** These road sections are at risk of moisture damage and the techniques have incorrectly predicted them as low risk road sections.

The first two groups are in the green category because they are the desired output from the risk analysis techniques. The latter two groups (False High/ False Low) are not desirable for any risk analysis and are in the yellow range in the matrix (Table 7-2).The performance indicators are adopted in this study based on their success in comparing the performances of the classification techniques (Vihinen, 2012; Sokolova & Lapalme, 2009; Schlotjes et al., 2014; Elzamly & Hussin, 2014). The indicators used in this research were adopted (Table 7-2) based on their relevancy to the objective of the comparative study and the characteristics of the risk analysis data (input and output). The performance indicators developed, based on the relationship of the above four groups of road sections in the matrix, include:

Precision: The precision denotes to the success of the risk analysis techniques in predicting the actual moisture damage risk of any road section. As seen in Table 7-2, the precision of a risk analysis technique has been calculated as the ratio of higher risk sites with the total road sections predicted to be at high risk (including a portion of the sites incorrectly predicted to be at high risk. The higher the precision value for a risk analysis technique the higher its success in predicting the higher risk road sections.

Sensitivity: This indicates the portion of the correctly predicted higher risk sections out of the total predicted road sections that are either truly predicted high or falsely predicted to be low (actually high). Therefore the sensitivity value indicates the portion the high risk road sections are correctly predicted.

Table 7-2 Performance Contingency Matrix and the Performance Indicators

		Moisture Damage Risk (Failure)	
		Risk (High)	Risk (Low)
Predictions	Risk (High)	True (High) (Th)[1]	False (High) (Fh)[2]
	Risk (Low)	False (Low) (Fl)	True (Low) (Tl)
Performance Indicators	Precision (p)	$p = \frac{Th}{Th + Fh}$	
	Sensitivity (r)	$r = \frac{Th}{Th + Fl}$	
	Specificity (s)	$s = \frac{Tl}{Fh + Tl}$	
	Negative Predictive Value (NPV)	$NPV = \frac{Tl}{Fl + Tl}$	
	Accuracy	$Accuracy = \frac{\sum(Th + Tn)}{N\,Total} * 100\%$	
	Prediction Error	$E = \frac{\sum(Fh + Fl)}{N\,Total} * 100\%$	
	F Score	$FScore = \frac{2 \times p \times r}{p + r}$	
	Matthews Correlation Coefficient (MCC)	$MMC = \frac{(Th \times Tl) - (Fh \times Fl)}{\sqrt{(Th + Fl)(Tl + Fh)(Th + Fh)(Tl + Fl)}}$	

[1] Success of the risk analysis techniques (Desired); [2] Failure in prediction (Not desirable)

Specificity: This is the ratio of the correctly predicted low risk sections in respect to the total predicted low road sections (includes a portion of incorrectly predicted high risk road sections) by the risk analysis technique. The specificity reflects on how many low risk road sections are predicted to be at low by the risk analysis technique.

Negative Predictive Value (NPV): The equation in Table 7-2 for the NPV indicates that it represents the portion of the low risk sections out of the total predicted low risk sections (some of which are high risk road sections incorrectly predicted to be low). Although it is opposite of precision, the NPV actually reflects the success of the risk analysis technique to identify the low risk road sections.

Accuracy and Prediction Error: These two performance indicators in Table 7-2, measure the success and failure of the risk analysis in predicting higher and lower risk road sections. The accuracy value (in percentage) indicates the percentage of road sections (green groups) correctly predicted out of the total road sections. The prediction error (percentage) value indicates the portion of incorrectly predicted (both high and low) road sections among the total toad sections. A higher accuracy along with low level of the prediction error is desirable for any risk analysis technique.

F-Score: The F-Score has been used as a performance indicator along with the accuracy and prediction error. It represents the weighted average of the precision and sensitivity values of a risk analysis technique in predicting the higher risk sites. It does not consider the success in predicting the low risk road sections. The F-Score values range from 0 to 1 and the higher the value (close to 1) the more accurate the risk analysis technique is in predicting the risk of any road section.

Matthews Correlation Coefficient (MCC): The MCC measures the agreement between the input and output of any risk analysis technique. The value of MCC is usually between -1 to 1. Any risk analysis technique of negative agreement (-1), indicates that the majority of the road sections are incorrectly predicted. On the other hand a positive agreement (+1) indicates the risk analysis is accurate in predicting the risk of the road sections (high and low). As the MCC considers both the correctly predicted higher and lower risk road sections, it therefore provides a better measurement of performance compared to the F-Score (Parker 2011; Powers, 2011 as cited in Schlotjes et al., 2014).

7.4.2 Data Set for Performance Evaluation

The strategy for data collection is crucial in comparative analysis because the data set should include a fair share of high and low risk road sections in the network. Due to the nature of the research project, data have been collected from the road network used in this study. A brief description of the road network was presented in Chapter 3. However, a representative sample of the road sections has to be selected for this comparative study because it is not feasible to include a large portion or the whole network. Rather, a comprehensive dataset of road sections is essential that can ensure a uniform distribution of high and low risk sites.

The road network is spread over a large region and the climate, geography, traffic volume, subgrade quality and drainage condition vary significantly among the road sections. In addition, the size of the sample road section also should not exceed a certain level because the amount of analysis involved in evaluating the three risk analysis techniques may not be practically feasible. Random sampling is one option for selecting the representative sample of the road network. However, it will be difficult to ensure an even distribution of the groups of road section through random sampling. Therefore, the stratified random sampling technique has been opted for in this study (Ayyub & McCuen, 2003). This sampling technique involves distributing the total population in a number of stratified sub-samples or groups. Then, a number of samples are randomly selected from the groups for each round of the analysis. By increasing the number of groups and rounds, it is possible to increase the acceptance validity of the comparative study (Ayyub & McCuen, 2003). Similar to the stratified sampling, cross validation sampling was employed to select the representative samples for evaluation of the classification techniques (Vihinen, 2012; Schlotjes et al., 2014).The criteria for selecting the sites for comparative analysis in the planned three rounds are presented in Table 7-3.

Table 7-3 Distribution of Road Sections and Sampling Criteria

Road Network	State Highway	Reference Section (no)	Treatment length (Km)/No of Sites	Selected Treatment Length (No) in 3 rounds	Comments (% of Road Sections)
West Waikato, South	A	1	10 (5.625)	3	54 out of 167 (32.3%)
		2	46 (20.15)	15	
		3	25 (20.06)	9	
		4	9 (5.730)	3	
		5	3 (2.05)	3	
		6	11 (11.52)	3	
		7	13 (11.67)	3	
		8	13 (15.66)	3	
		9	10 (14.35)	3	
		10	10 (14.62)	3	
		11	4 (7.7)	3	
		12	13 (17.2)	3	
	B	1	8 (15.45)	3	6 out 0f 18 (33%)
		2	10 (19.77)	3	
	C	1	12 (14.61)	3	12 out of 35 (34.3%)
		2	7 (15.68)	3	
		3	10 (16.35)	3	
		4	6 (14.05)	3	
	D	1	11 (13.61)	3	12 out of 32 (37.5%)
		2	7 (17.25)	3	
		3	8 (16.15)	3	
		4	6 (9.30)	3	

	E	1	4 (7.35)	3	3 out of 4 (75%)
	F	1	13 (15.15)	3	12 out of 37 (32.4%)
		2	7 (9.65)	3	
		3	17 (15.27)	6	
Total	6	25	291	99	34% of the Total Sites

The road network includes six State Highways in the north-western part of New Zealand. Each State Highway is divided into a number of reference stations/segments. Due to confidentiality requirements the actual numbers of State Highway and reference stations are avoided. Each reference station usually begins from the north. There are a number of treatment lengths/sites in each reference station as in the 4th column in Table 7-3. A total of three rounds of comparative analysis were conducted and approximately one-third of the treatment length/sites were randomly selected from each reference station of the network. Therefore, 99 road sections of varying length were randomly selected in those three rounds, out of the total 291 sites of the network. The road sections selected for comparative analysis are roughly around one third of the total road sections. Therefore the amount of road sections covered in the study should be rational because of the level of data collection, physical or video survey and human input required for assessment of the road sections in the network. Overall the reference stations are evenly distributed over the network, this form of stratified sampling should ensure a uniform coverage of the network features such as geography, terrain, traffic volume, drainage catchment, subgrade conditions and pavement conditions in each round of analysis. Overall, the number of road sections selected for each round of the analysis is expected to ensure all possible types of road sections as per the performance contingency matrix (Table 7-2).

7.4.3 Performance Evaluation of the Risk Analysis Techniques

The comparative analysis of the risk analysis techniques was implemented in three rounds among the equally distributed road sections selected from the road network. The actual status or true moisture damage risks (high/low) of the road sections were detected based on their relative status in the forward work programme, historical maintenance cost and condition parameters (pavement distresses). The actual status of a road section based on the FWP, maintenance cost trend and the pavement condition rating has been demonstrated in the case studies in Chapter 9. Then the sites or road sections were assessed through the risk analysis techniques and the output of the performance measurement is presented in Table 7-4.

Table 7-4 Summary of the Comparative Analysis of the Risk Analysis Techniques

Risk Analysis Techniques	Round	Precision	Sensitivity	Specificity	Negative Predictive Value	Accuracy	Prediction Error	F-Score	MCC	Comments
Fuzzy Logic Model	1	0.95	0.95	0.92	0.92	94%	6%	0.96	0.88	
	2	1.0	0.92	1.0	0.82	94%	6%	0.96	0.87	
	3	0.95	1.0	0.93	1.0	97%	3%	0.97	0.94	
Fault Tree Analysis	1	0.81	0.85	0.69	0.75	79%	21%	0.83	0.55	
	2	0.95	0.83	0.89	0.67	85%	15%	0.89	0.70	
	3	0.88	0.83	0.87	0.81	85%	15%	0.86	0.70	
Combination of Moisture Damage Factors	1	0.90	0.90	0.85	0.85	88%	12%	0.90	0.75	
	2	0.96	0.92	0.89	0.80	90%	10%	0.94	0.78	
	3	0.84	0.89	0.80	0.86	85%	15%	0.86	0.70	

The output of the comparative analysis is presented in Table 7-4. A total of 33 road sections randomly were selected from the 25 evenly distributed road segments (reference stations) in each round. Thus 99 road section moisture damage risks have been assessed through the three risk analysis techniques. The performance contingency matrix was developed based on the predicted risk compared with the actual status of the road section. The performance indicators were calculated based on the equations in Table 7-2. The Table 7-4 presents the 8 point performance indicators to evaluate the performance of the risk analysis techniques.

Overall, the performances of all the risk analysis techniques were satisfactory, providing the level of accuracy ranges from 79% to 95%. In terms of accuracy and prediction error, the fuzzy logic model yields the best performance with the number of falsely predicted sites less than 10%. The average prediction error of the FTA was 20%, which reduces its level of performance. This is because the moisture damage factors were assumed to be inconclusive and their probabilities keep on accumulating, although in practice the pavement condition and maintenance costs do not reflect the predicted risk status of the road section. The combination of expert judgment technique also performs well in predicting moisture damage road risk with an average accuracy of 88%. Therefore, the fuzzy logic model outperformed the other two techniques in respect of high accuracy and low level of prediction error.

The precision and NPV value represent the ability of the risk analysis techniques to predict the actual risks (high or low) of the road sections. In this case, both the precision and NPV values indicate the success of the risk analysis techniques in predicting the true risk. The value of these two indicators range from 0 to 1 and higher values indicate better performance of the risk analysis technique. The precision values of the risk analysis techniques were comparatively higher than the NPV values. This indicates that the risk analysis techniques perform well in predicting higher risk road sections. This may be a road section predicted to be high due to the factors class, volume of traffic, age of the pavement and geography however, they are performing well (actual low). The road network is under constant monitoring and regularly maintained due to the nature of the road maintenance contract. Thus the prediction of the risk of some road sections may differ from the actual perceived risk based on the forward work programme, maintenance cost and pavement condition rating.

The F-Score is the weighted average of the precision and sensitivity and represents the ability of the risk analysis techniques to predict the higher risk road sections. It does not include the calculation of low risk road sections. This could be particularly important to the practitioners who are more concerned with the road sections that are at high risk. The higher the value of the F-Score, the better the performance of the risk analysis technique in predicting the high risk road sections. The fuzzy logic model performs better compared to the other two techniques in predicting the high risk of road sections. Overall, all three risk analysis techniques perform well in respect of F-scores. This is considered acceptable because the risk analysis techniques are subjective and assess the road sections based on the trigger based on moisture damage parameters as described in the previous three chapters where the risk analysis techniques were demonstrated.

The MCC values of all three risk analysis techniques were greater than zero, indicating that the outputs are positively associated with the input of the risk analysis techniques. MCC is a well-accepted indicator for evaluating the performance of the classification techniques (Vihinen, 2012; Sokolova & Lapalme, 2009). A perfect MCC value of 1.0 indicates that the risk analysis technique is perfect in predicting the risk of the road sections. The average MCC value (0.965) for the fuzzy logic model is close and indicates that the output of the risk analysis technique is in agreement with the inputs and is very close to perfectly predict the risk of the road sections. The average MCC of the combination of expert judgment is slightly higher than the FTA. However, the average MCC of 0.68 for the FTA indicates the relative disagreement between the inputs and output of the risk analysis technique.

Based on the above discussion and the evaluation of the performance indicators (Table 7-4), it can be advised that all three risk analysis techniques are capable of predicting the moisture damage risk of the road sections. The risk analysis techniques perform well in predicting high risk road sections. The performances of the risk analysis techniques do not vary significantly, rather they are close to each other in terms of prediction capability and the association between the inputs and output. However, the risk analysis techniques are ranked in the following order based on their difference in the prediction error, F-Score and the MCC values in Table 7-4.

1. Fuzzy Logic Model
2. Combination of Moisture Damage Factors
3. Fault Three Analysis

7.5 Comparative Analysis Based on Technical and Practicality Features

The previous section evaluated the performances of the risk analysis techniques. It is not practical to select the optimum risk analysis technique based on the differences in their performance alone. Therefore, this section extends the evaluation process based on some additional requirements of the risk analysis techniques. Table 7-5 summarises some of the features used in research studies to evaluate the classification techniques or developed software in addition to the performance.

Table 7-5 Summary of Features used in a Number of Study

Research/ Study	Features Used for Evaluation of the Techniques/Software
Aniba, Poch, & Thompson (2010) and Gray (1993) as cited in Vihinen (2012)	Test of applicability, reliability, availability, relevance, accessibility, representativeness, non-redundancy reusability
Elzamly and Hussin, (2014)	Lack of traceability, confidentiality, correctness, mismatch, missing detailed requirement analysis, Inadequate knowledge of the tools/lack of adaptability
Schlotjes et al. (2014)	Running speed, ease of use, interpretability and avoids over fitting

Based on the above review of the literature, the evaluation of the risk analysis techniques was further modified to the following criteria that include a set of additional features:

- Develop a ranking of the risk analysis techniques based on the performance indicators in Table 7-2;
- The risk analysis technique should be easy to understand and implement within a reasonable time frame. The technique has to be readily available at minimum cost and it should have the ability to produce repeatable results of risk analysis;
- In addition, the optimum risk analysis technique is expected to be developed with the least amount of limitations. Finally, the risk analysis technique has to be easily understood by the experts and practitioners and adaptable to the existing practices in commercial road network maintenance activities, especially with the drainage needs assessment.

7.5.1 Implementation Time

The speed of the risk analysis techniques is crucial for their performance in the MDRA framework. Therefore, the optimum risk analysis technique is expected to perform the analysis within the least possible time. Table 7-6 summarises the aspects of the risk analysis techniques in terms of implementation time.

Table 7-6 Comparative Study of the Risk Analysis Techniques (Implementation Time)

Fuzzy Logic Model	Fault Tree Analysis	Combination of Moisture Damage Factors
The most time consuming part in fuzzy logic is to set up the model in the Fuzzy Inference Editor toolbox in Matlab. Usually it takes an hour to set up the inputs and output of the model and their membership functions. If the membership functions of the model are determined based on expert judgement, then it does not involve much time to set up this in the model. Another way is to set up the membership function based on judgement and finalise it based on trial and error after the evaluation of the risk assessment output. The inference rules are required to be entered into the model. The 'If-Then' based inference rules have to be road network specific and expected to perform well if finalised through consultation with the network experts. The consultation process should be done during the data accumulation stage so a fuzzy logic model for any road network should be ready to use within two hours. It requires 2 to 3 minutes to assess the moisture damage risks of 10 road sections (100 m) by the fuzzy logic model. The analysis has to be done manually and it is a monotonous task, so	The Fault tree analysis technique used in this study for risk assessment is different from the other two techniques. The risk analysis through FTA varies due to the age of the pavement. If the pavement is relatively new, or recently rehabilitated, then it is considered for early pavement damage risk only. Fault trees developed for the early pavement damage are used to identify the critical failure paths and a qualitative risk assessment for reporting purposes. The time required for this assessment will vary for different experts. However, the analysis is subjective; hence each 100 m road section may require quarter of an hour if all of the moisture damage parameters are readily available. On the other hand, the old road pavements are assessed to predict the possible risk of moisture damage within the life cycle. This assessment can be conducted both qualitatively and quantitatively based on the requirement of the network owner. The qualitative assessment of moisture damage factors and the failure paths using the fault tree for permanent pavement damage will require a similar time frame for the early pavement damage. In order to identify the probability of the permanent moisture damage of a road section, two distinctive methods were	This risk analysis model is developed using the Microsoft Excel add-in "Model Risk" developed by Vose Software. The tasks required in this method to accumulate the moisture damage factor related data are similar to the fuzzy logic model. This risk analysis method is applicable to identify the combined risk rating of the treatment length based on the combination of the moisture damage factors by the experts. A treatment length of 1 km is composed of ten 100 m road sections. For each moisture damage factor, there will be 10 values to be entered into the Microsoft Excel sheet. The number of values will be increased if shorter road sections are considered. It takes roughly around 2 to 3 minutes to enter the total moisture damage factor values of a site in the excel sheet. Once entered, the data viewer can generate the distributions within a minute. The minimum, maximum and mode values of the distributions have to be entered for the combined distribution curve for a particular treatment site. The weighting of the factors can be changed if required. The combined curve can generate the risk rating based on any percentile value as deemed suitable by the network experts. All of these steps can be

Fuzzy Logic Model	Fault Tree Analysis	Combination of Moisture Damage Factors
to avoid any error, sufficient interval has to be ensured during the analysis.	demonstrated in Chapter 5. Usually it takes around 3 to 4 hours to set up the fault tree with the online fault tree analyser developed by ALD. There are a number of parameters such as failure rate and analysis period that have to be predetermined based on the network performance and expert judgement. Once the fault tree is developed the individual analysis of each road section takes only a few minutes to process. The excel template developed to identify the probability of moisture damage risk of road section is relatively fast to set up and it can be modified within a short time period. Here the number of probable damage per kilometre due to a moisture damage factor has to be assumed or measured on site during the inspection. This process requires due diligence and time to identify the probable number of damages induced due to any moisture damage factors. The probability calculation requires negligible time, however, a brief statement on the failure path and the likelihood (probability) and the consequence is essential.	linked to an excel sheet so the calculations can be automated. The requirement is to enter the moisture damage values in the excel sheet. If the automation is set up this risk analysis method can generate the combined risk rating of an entire length within the least possible time of all the analysis techniques.

The comparison of the time required for the three risk analysis techniques is not straightforward. The methodology and the output of the risk analysis techniques vary considerably. Any of the risk analysis techniques can be deemed suitable based on the network requirement. In respect of risk analysis of a 100 m road section, the fuzzy logic model can generate the risk rating within the least time. However, it does not involve any explanation of the failure path or the critical path. The risk assessment of the entire treatment length (rating) can be identified by the combination of expert judgement method within the shortest possible time. Generally the FTA technique involves a thorough investigation of the moisture damage factors of any road section to identify the critical path and the probability of failure.

7.5.2 Availability and Transferability of the Techniques

The terms ‘availability’ and ‘transferability’ are important in respect of the inclusion of the risk analysis techniques into the MDRA. As the MDRA is expected to predict the moisture damage risks of road sections, so the technique should be reliable and reusable at different stages of road asset management. Although the reliability refers to the performance of the risk analysis techniques, factors such as availability and capability to modify, can be used to distinguish the techniques. The ability to reuse the risk analysis techniques in moisture damage risk assessment is also crucial in road network management. The comparative statements of the risk analysis techniques in respect of availability and transferability are presented in Table 7-7.

Table 7-7 Availability and Transferability of the Risk analysis Techniques

Fuzzy Logic Model	Fault Tree Analysis	Combination of Moisture Damage Factors
A. Availability		
The fuzzy logic model in this study is available in the Matlab toolbox. Matlab is a widely used programme and this particular tool is also available for download from its packages. However, it requires a commercial licence to use the programme for road maintenance purposes.	The fault trees used for risk analysis are developed based on expert judgement and literature review. The qualitative analysis does not involve any software. An expert on the road network can assess the risk of any road section by visual inspection, test pits, and pavement strength data. Two different methods were demonstrated to identify the probability of failure. The online fault tree software from ALD can be used for education and research purposes as free of charge. The software is expensive for commercial use in road network maintenance.	This risk analysis is developed in the 'Model Risk' programme, developed by Vose Software Ltd. Model Risk works as an add-to the Microsoft Excel and uses the principle of superposition to identify the combined distribution of the treatment length. Based on the characteristics of the moisture damage factors (ratings on the scale of 1 to 10), the tool to combine their distributions in the 'Model Risk' programme has been utilised. The software is not expensive for commercial uses in road network maintenance.
It involves a certain amount of technical expertise to set up the fuzzy logic model. Once the model is set up, it does not involve much expertise to use the model for risk analysis. This model can be modified to implement in any road networks of varying geophysical background, weather, pavements, traffic and drainage conditions. However, it requires a significant amount of experts' effort to modify the model for any particular road network.	The Microsoft excel template developed, requires the estimation of the failure rate in the probability calculation. The expert needs to comment on the possible time (year) required for moisture damage due to a root cause. This may involve a significant subjective judgement of the expert and can be difficult to in some instances to estimate a realistic failure rate (moisture damage/ year) of a root event.	Once the combined distribution curve of the moisture damage factors is set up, little expertise is required to perform the risk analysis. The risk analysis technique can be modified for use in any other road network with limited effort.

Fuzzy Logic Model	Fault Tree Analysis	Combination of Moisture Damage Factors
Both the fuzzy logic model and the combination of the expert judgement (Model risk) are available through commercial licensing. These programmes are not commercially expensive. Whereas, the fuzzy logic model is developed as a toolbox in the Matlab software. The platform of this programme is different from the usual application programmes used for road network maintenance purposes (Microsoft Office). Thus the analysis in the fuzzy logic model has to be done separately and conducted manually.	The FTA technique used in this study has been demonstrated to utilise two different platforms for estimation of probability of risk. The free online fault tree analysis software is used for risk (probability) assessment. This version is a one-off use of the developed fault tree with no reusing capability. The commercial version of this software has been utilised in different sectors for risk analysis. The inbuilt fault trees in the software do not match with the failure mechanisms in the road pavement. Therefore, the fault tree developed in this study was trialled and applied for moisture damage risk assessment. The online FTA can be used by procuring the commercial license of this programme. However, the fault trees, necessary estimation methods and criteria need to be set up in the programme for risk analysis. The Microsoft excel template developed in this study for FTA, has been demonstrated for the assessment of moisture damage risk. It involves an estimation of the probability with the failure rate of a root cause (Equation 5-4). The failure rate has been calculated based on the estimated time (year) required to cause a damage (failure) by any root cause. This estimation is a key component of these risk analysis techniques so it requires a higher level of verification of the risk analysis technique.	Both the fuzzy logic model and the combination of the expert judgement (Model risk) are available through commercial licensing. These programmes are not commercially expensive. The Model risk is an add-in to Microsoft Excel which is used for database collection in most organisations. The Road Assessment, Maintenance and Management (RAMM) database stores and manages all necessary information on road network maintenance in New Zealand. The data extracted for road network maintenance from the database can be downloaded into excel files. These data can be used by the model risk programme.

Fuzzy Logic Model	Fault Tree Analysis	Combination of Moisture Damage Factors
B. Transferability		
The fuzzy logic model was found to provide repeatable moisture damage risk data of road sections in the least possible time. The model does not require any change for different roads in a network. If the geology, pavement type, drainage and climate of road sections do not vary significantly, the model can reproduce or be reused for moisture damage risk assessment of any road section.	The FTA risk analysis requires more time for risk assessment compared to the other two techniques. It requires an expert to assess the road section in respect of the fault tree and identify the failure paths. The FTA can be reused for qualitative risk assessment purposes efficiently within a short time period. The quantitative assessment of moisture damage risk using the FTA is a lengthy process compared to the other two techniques. The FTA has the least capacity to repeat the moisture damage risk assessment in a road network. However, the risk analysis technique can be used to identify both the probability of moisture damage risk along with the failure paths.	This risk analysis technique can be repeated for risk assessment efficiently within a short period of time. The reproducibility of the risk analysis technique is less than the fuzzy logic model and higher than the FTA. The model does not require excess modification to use in different roads in a network. The model can be reused for moisture damage risk assessment of different road networks effectively. The reusability of the technique depends on the type of operation. If the risk analysis has to be conducted manually, then it takes almost similar time to FTA.

7.5.3 Limitations of the Techniques

Table 7-8 summarises the comparative assessment of the risk analysis techniques in respect of the limitations. The limitations of the risk analysis techniques have been presented in four categories such as general limitation, assumptions of the techniques, types of operation and transparency.

Table 7-8 Comparative Statement of the Risk Analysis Techniques based on the Limitations

Fuzzy Logic Model	Fault Tree Analysis	Combination of Moisture Damage Factors
A. General Limitation		
The fuzzy logic model is more applicable for smaller road sections. The moisture damage factors in smaller road sections can be represented by a single expression or a rating on a scale.	The FTA is applicable to both the smaller road sections and the whole treatment length. For smaller road sections the number of failure paths can be less. The whole treatment length or site may have multiple failure paths with a few critical ones. The critical	This technique is difficult to apply for risk assessment of smaller road section. In order to develop the distributions of the moisture damage factors, there must be a number of road sections. For example, a

Fuzzy Logic Model	Fault Tree Analysis	Combination of Moisture Damage Factors
The geophysical factors may change frequently in a long or whole treatment length or site, so it is not practical to express these factors by a unique rating. Rather, a distribution curve for the factors of the 100 m road sections of the site would be more suitable.	failure paths are essential during forensic investigation of any premature failure. The failure paths of any road section are used to determine the probability of failure or risk of moisture damage. However, the road section should not exceed a certain threshold to avoid overestimation of the probability of failure risk.	100 m road section can be subdivided into shorter road sections. However, these may not be feasible because the moisture damage parameters of the road section may not vary, therefore, the distributions will not be realistic. Rather, it is applicable for risk assessment of the whole treatment length, which can be subdivided into a number of smaller road sections (100 m).
B. Assumptions of the Risk Analysis Techniques		
The fuzzy logic and the 'combination of expert judgement' techniques in the study incorporated the least amount of assumptions. In the fuzzy logic model, the trapezoidal and triangular membership functions are used to define the inputs (moisture damage factor) and the output of the risk analysis model. These membership functions were utilised in different research studies in various sectors (Rezakhani, 2012; Zlateva et al., 2011).	The FTA technique included a number of assumptions. No assumption is required for qualitative risk assessment in FTA. On the other hand, the estimation of probability in quantitative risk analysis included a number of assumptions. In order to calculate the probability of failure using the online fault tree analysis programme, the analysis period is assumed to be 5 years. The risk of early pavement damage is estimated for newly rehabilitated pavement and the objective is to find out road sections that are at risk of failure within the first five years. On the other hand, the permanent pavement damage risk is calculated for old road pavement which is either at the middle or end of the life cycle. The FTA with the Microsoft excel template developed in this study, assumed that the probability of failure due to a root cause may have a relationship (Equation 5-4) with the estimated failure rate (moisture damage per hour). Generally, the factors related to surface failure assumed to induce less moisture damage compared to	The fuzzy logic and the 'combination of expert judgement' techniques in the study incorporated the least amount of assumptions. In this technique, the PERT (Project Evaluation and Review Technique) distributions were used to represent the distributions of the moisture damage factors (ratings). The PERT distribution is well developed and also used in simulating project and construction risks in various sectors.

Fuzzy Logic Model	Fault Tree Analysis	Combination of Moisture Damage Factors
	the sub-surface, drainage, pavement and traffic volume in road section. In addition, these factors are not mutually inclusive, so any of the factors can contribute to the final probability of failure. Overall, the FTA technique has been developed based on a number of assumptions, especially, to estimate the failure rate.	
C. Types of Operation		
The fuzzy logic model is comparatively better than FTA in terms of the mode of operation; however, it is not fully automated. The model itself requires a moderate amount of effort. However, the rule viewer can yield the risk rating based on the ratings of the factors with limited manual operation. The fuzzy logic model has the best ability to reproduce risk rating for multiple road sections within a limited time and effort.	The FTA is the least favoured technique in respect of automation. It incorporated qualitative risk assessment which can be useful for forensic investigation of a road section for premature failure. This involves a moderate amount of expert involvement in developing the fault tree based on the root causes present in that section. The quantitative risk assessment by FTA also involves developing the fault trees, identifying the failure types, concerned failure rate, time of analysis and estimation of the amount of moisture damage in a road section. These involve a significant amount of manual entry and assessment tasks for risk analysis.	In terms of the mode of operation, the most efficient technique is the ‘Combination of Expert Judgement’ method. The ‘Model Risk’ platform used for this technique has the capability to set up links among the different steps in risk analysis. This helps the risk technique to be more efficient compared to the other techniques. Once these links are set up, a user has to enter the value of the moisture damage factors into an excel sheet based on the moisture damage parameters. The model can produce the combined curve for the whole treatment length based on the moisture damage factors of the 100 m road sections. However, the final risk rating has to be extracted manually based on the percentile value as suggested by the network controlling authority. This semi-automated characteristic of the technique increases its capacity to reproduce the moisture damage risk of multiple road sections.

Fuzzy Logic Model	Fault Tree Analysis	Combination of Moisture Damage Factors
D. Transparent to the User		
This risk analysis technique is a ‘black box’ which includes a set of inference rules based on expert judgement. Although the inference rules guided the simulation technique, there involves a set of mathematical calculations based on the membership functions and the fuzzy inference rules in the model.	The FTA is more transparent to the user compared to the other risk analysis techniques. The basis of FTA is the fault trees which show the association among the root causes and their effect on the predicted fault. The probability estimation technique based on the online fault tree analysis programme is not solely open to the user. However, it is well demonstrated and it uses the basic theories of probability calculation.	This risk analysis technique is more transparent than the fuzzy logic model. As all of the risk analysis techniques involve the estimation of moisture damage factors based on their parameters, their transparency depends on the theory and the calculation of the technique. This risk analysis technique works on the basic principle of superposition. The distribution curves of the moisture damage factors are superimposed to generate the resultant curve. The estimation of final risk rating based on the combined curve includes a certain degree of complexity compared to the FTA.

7.5.4 Applicability of the Techniques in Drainage Needs Assessments

Drainage needs assessment is a vital component in road asset management. Various drainage improvement and maintenance programmes are targeted to drain water out of the pavement and also to reduce excess water entering and within the pavement. Therefore, the objective of positive drainage is to increase the life cycle of the pavement through reducing the water from the pavement formation (NZTA, 2014). In New Zealand, road controlling authorities have a number of drainage improvement programmes such as in Table 7-9.

Table 7-9 Major Drainage Programme in New Zealand

Programme	Functions of the Drainage Measures
Installation of new sub-soil drain and drop chamber	The function of sub-soil drains is to prohibit the flow of sub-surface water into the pavement formation, especially at cut and fill and box-cut sections. The sub-soil drains are to cut off the high ground water table in a box cutting road section. The drop chamber is to hold the water from the sub-soil drains and to increase the retention capacity of the ground water.
Install or repair of kerb and channel	The kerb and channel is installed mostly in urban areas, in cut and fill and in box cutting road sections. The prime function of the kerb and channel is to retain and remove the thin film of surface water into the storm water system or streams through the catch pit, drop chamber and culvert system. The kerb and channel are essential in urban roads and in rural roads where there is inadequate shoulder and storm water channels.
Reform storm water channel	The function of the storm water channel is to carry the water from the pavement to the natural stream or surrounding reservoir. Over time this storm water channel gets clogged due to vegetation, siltation and deposition of rubbish. This may block the water flow and causes stagnant water on the side of the pavement or occasional flooding. Water may infiltrate into the pavement due to flooding or stagnant water on the side drain. This may induce a wet shoulder, edge break, wheel path rutting. So the road side drain should be maintained to avoid any blockage or overflow.
High lip Removal	The High lip occurs because of high shoulder, depression of wheel path and excess vegetation on shoulder. This High lip usually causes blocked water on wheel path and induces risk of aquaplaning. Removal of this HI-Lip is an important programme undertaken by road network controlling authorities in New Zealand.

The major drainage maintenance programmes in New Zealand described in Table 7-3, are targeted to remove the water out of the pavement surface and sub-surface. The overall objectives are to keep the road pavement dry, free from excess water and thus to increase the life cycle of the road pavement. Therefore, the drainage needs assessment is required to identify the road sections where the stipulated drainage programme can be implemented. The MDRA is planned to be the framework that can be used to locate the road sections where these programmes can be allocated to improve the drainage of the road pavement and thus to reduce the risk of premature failure (due to moisture damage). The risk analysis techniques in MDRA are expected to meet the requirement of the network drainage needs assessment.

Among the three risk analysis techniques, the fuzzy logic model is more compatible with the drainage needs assessment. This model provides the ratings and linguistic expressions of moisture damage risk of 100 m road sections. This will help in developing the drainage risk profile of any treatment length. In addition, the output of the fuzzy logic model can be used for prioritisation of the drainage programmes. Any treatment length analysed through the fuzzy logic model might possess two or three 100 m road sections of very high risk. These high risk road sections can then be targeted for drainage improvement. In addition, the moisture damage factors in the fuzzy logic model can be useful for selecting the optimum drainage programme for any particular road section. However, it is not feasible to use fuzzy logic model for risk assessment of longer sites as the moisture damage factors may vary significantly over the road sections.

On the other hand the ‘Combined distribution technique’ can be used for risk assessment of longer sites. Because this model incorporates the distribution of moisture damage factors of the 100 m road sections of a treatment length. The resultant curve can then be used to predict the risk rating of the whole treatment length. The risk rating of the whole treatment length is also essential in road network management. Usually a road network is divided into a number of treatment lengths or sites for long term planning of maintenance programmes. Therefore, the risk ratings of the treatment lengths will help in developing the forward work programmes for drainage improvement.

The FTA technique is applicable for assessment of both the short and the long term drainage needs of a road section. The predicted risk might be overestimated for longer treatment length. The highlight of this technique is that it describes the root causes and their association in causing the premature failure in road pavements. Thus, the FTA is more applicable for forensic investigation of any road section for premature failure and to develop the short and long term strategies to reduce the risk of failure. The estimation of probability can be used to prioritise the drainage programmes. The sites with higher probability of failure due to moisture damage should be selected for immediate drainage improvement. The fault trees can be used to select the optimum drainage improvement for a road section based on the critical failure path. However, the risk analysis technique requires more time for risk assessment compared to the other two techniques.

7.6 Summary of the Comparative Analysis

The risk analysis techniques are ranked based on the performance assessment, technical and practical features presented in previous sections and summarised in Table 7-10. They are scored on a scale of 1 to 3, where 1 being the most favoured and 3 indicates the least favoured risk analysis technique. The ranking of the techniques is conducted based on the performance assessment in Section 7.4 and the comparative statements in Section 7.5 of this Chapter. The objective of the qualitative ranking is to identify the optimum risk analysis technique for the MDRA.

Table 7-10 Summary of Comparison of the Risk Analysis Techniques

	Comparative Assessment of the Risk Analysis Technique			
Features	**Fuzzy Logic Model (A)**	**Fault Tree Analysis (B)**	**Combination of Moisture Damage Factors (C)**	**Preferred**
Ranking based on Performance Indicators	1	3	2	A
Speed of the Risk Analysis Techniques	1	3	2	A
Reproducibility and Reliability	1	3	2	A
Adaptability with Road Asset Management	1	2	3	A
Limitations	1	3	2	A
Assumptions	2	3	1	C
Comprehensiveness of risk assessment	2	1	3	B
Types of Operation	2	3	1	C

	Comparative Assessment of the Risk Analysis Technique			
Transparency	3	1	2	B
Compatibility with the drainage needs assessment	1	3	2	A
Total	15	25	20	A

The comparative analysis indicates that the fuzzy logic model received the lowest score so is the most optimum among the risk analysis techniques. The fuzzy logic model performs well in predicting moisture damage risk rating of smaller road sections. It is the most efficient risk analysis technique that can predict multiple road sections of a network within the shortest time. The level of assumptions and the limitations of the technique are minimal compared to other techniques. However, the fuzzy logic model is not open to the user and may not be suitable for risk assessment of longer treatment lengths. The risk rating in this technique gives a predictive framework; however, it is not comprehensive like the FTA. The FTA technique on the other hand gives a probability based prediction framework along with the descriptive statement of the root causes and the failure paths. Given the higher limitations and assumptions, excess time required for implementation, and the lack of capacity to reproduce the reliable risk assessment data, the FTA is seen as the least favoured technique. It is preferable for detailed investigation of a road section for premature failure and drainage risk assessment. The ‘combination of the moisture damage factor’ technique received a moderate ranking in respect of the features of the comparative analysis. This risk analysis technique can be favoured for the assessment of an entire treatment length composed of a number of 100 m road sections. This is also a closed model with the capability to reproduce the risk ratings of multiple road sections.

7.7 Summary

The risk analysis techniques are scrutinised based on their performance, speed, reliability, reproducibility, openness to the user and adaptability in road asset management. The fuzzy logic model and the combined distribution of expert judgement are found to be the favoured risk analysis techniques. The fuzzy logic model is the optimum technique for assessment of shorter road sections. The combined distribution of the moisture damage factors is also applicable in MDRA, especially to predict the risk rating of longer treatment lengths or multiple road sections (100 m). The next chapter provides the development and evaluation of the revised MDRA framework based on the feedback of the practitioners and the comparative analysis of the risk analysis techniques.

Chapter 8: Development and Evaluation of the MDRA

8.1 Introduction

This chapter demonstrates the development and evaluation of a risk assessment framework (MDRA) which is designed to identify the road sections that are at risk of failure due to moisture damage. The outcome of the risk assessment can help to generate the drainage needs of the road network. The chronological development of the MDRA framework was presented in the previous chapters. The framework has been modified based on the feedback of the practitioners, and knowledge obtained during the assessment and comparison of the risk analysis techniques. Therefore the application of the framework in drainage needs assessment is demonstrated in this chapter. In addition, the framework has been evaluated based on its ability to predict the moisture damage risk of the road sections. Case studies were conducted to evaluate the validity of the framework in relation to some established prioritisation framework (FWP, pavement condition trends, and maintenance cost trends) in road network maintenance. These prioritisation frameworks are used in New Zealand for developing the long term planning of the maintenance works in road networks (NZTA, 2014). Therefore, a brief review of the frameworks along with the evaluation of the MDRA in respect of them is presented in later part of the chapter.

8.2 Moisture damage Risk Assessment Framework (Revised)

The MDRA was developed through a background study, and literature review, preliminary field work and an iterative process of trial and error during the three years of the research. The background literature search provided a strong platform, to evaluate the effect of moisture in flexible road pavements. The preliminary study, conducted in 2012, identified the factors responsible for moisture damage in road pavements. Based on the literature review and the preliminary study, the risk assessment framework (MDRA) was formulated (Mia et al., 2013, 2014). The MDRA was disseminated in a number of forums and to experts in the field of road maintenance. The feedback received from experts and participants in those forums was helpful in developing the refined form of the MDRA.

The moisture damage factors identified within the course of the research are classified as either static or dynamic as presented in Table 8-1. The static factors are classified as 'geophysical' or related to the 'pavement profile'. Such factors rarely change over time and usually pose a steady risk to road pavement deterioration. The dynamic factors are 'road classification and pavement strength' and the 'drainage risk factors'. These parameters change over time and possess a different amount of risk at different stages of the life cycle of any road pavement. The background studies helped to identify the root causes of the moisture damage factors and were termed as 'Moisture Damage Parameters'.

Table 8-1 Moisture Damage Parameters (Identify Inputs for Risk Assessment)

Category	Moisture Damage Factors	Moisture Damage Parameters (Root Causes)
Static	Geophysical Factors	Side hill next to road pavement (Within 10 m)
		Stream/Source of Open Water within 10 m of Road Pavement
		Bush area/Vegetation Blocking the Drainage (Next to Shoulder)
		Road Section at Vertical Sag
		Road Section at Flooding Areas (History of Flooding)
	Pavement Profile	Topography (Flat/Rolling)
		Pavement Profile (if at cut-and-fill and box-cutting)
		Road Section at High Stress Areas (Including Start-Stop areas)
		Poor Shoulder Materials
Dynamic	Road Classification and Pavement Strength	Sensitive Subgrade (PI>25)
		Weak Pavement layer (Based on Do value of FWD test)
		Thin/ Old surfacing layer
		Old/ Recycled Pavement Layer
		Poor base course layer (High PI)
		Road section with high AADT (More than 5,000 vpd)
		Excess heavy commercial vehicles (More than 15%)
	Drainage, Shoulder and Weather	Inadequate cross fall (Flat Road)
		Kerb and channel blocked/damaged
		Non-functional sub-soil drain
		Rainfall high
		Cross culvert (if any) faulty
		Old seal layer, causing water trapped under the new overlay
		Water table high (less than 1 m from ground level) Inadequate/Unsealed Shoulder

The moisture damage parameters in Table 8-1are perceived to generate triggers which will be used to identify the linguistic expressions of risk factors and the ratings based on the field expert's judgment. Each of the parameters raises a trigger and the total number of triggers yielded the rating of the moisture damage factor. A technical seminar was conducted with the managers and practitioners of the road network maintenance. The objective of the seminar was to disseminate the development of the risk assessment framework and receive their feedback of the participants. The practitioners were seemed to be concerned with the road sections at higher risk; therefore any section with less than 6 triggers in total will be excluded from the detailed risk assessment. Road sections with between 6 and 12 triggers will be considered as 'High', whereas, greater than 12 triggers will be perceived as 'Very High' risk of moisture damage. These two categories of road sections will be further scrutinised based on the framework presented in Figure 8-1.

The preliminary framework of MDRA presented in Mia et al. (2014) and the updated one presented in Figure 8-1 are fundamentally on the same principle. The basic principle of the MDRA is to predict the risk of failure due to moisture damage of road pavements and present the risk either by a linguistic expression or a rating. Initially the three candidate risk analysis techniques (Fuzzy Logic Model, Combined-Distribution and FTA) were trialled to identify the optimum technique for the MDRA. After an extensive evaluation in Chapter 7, these three candidate risk analysis techniques have been considered to be complementary to each other. Therefore, they have been included with different functions in risk assessment at different stages of the life cycle of a road pavement (Figure 8-1). The framework of MDRA has been formulated to be easy and self-explanatory and its application has been demonstrated while implementing the framework in risk assessment in the next section.

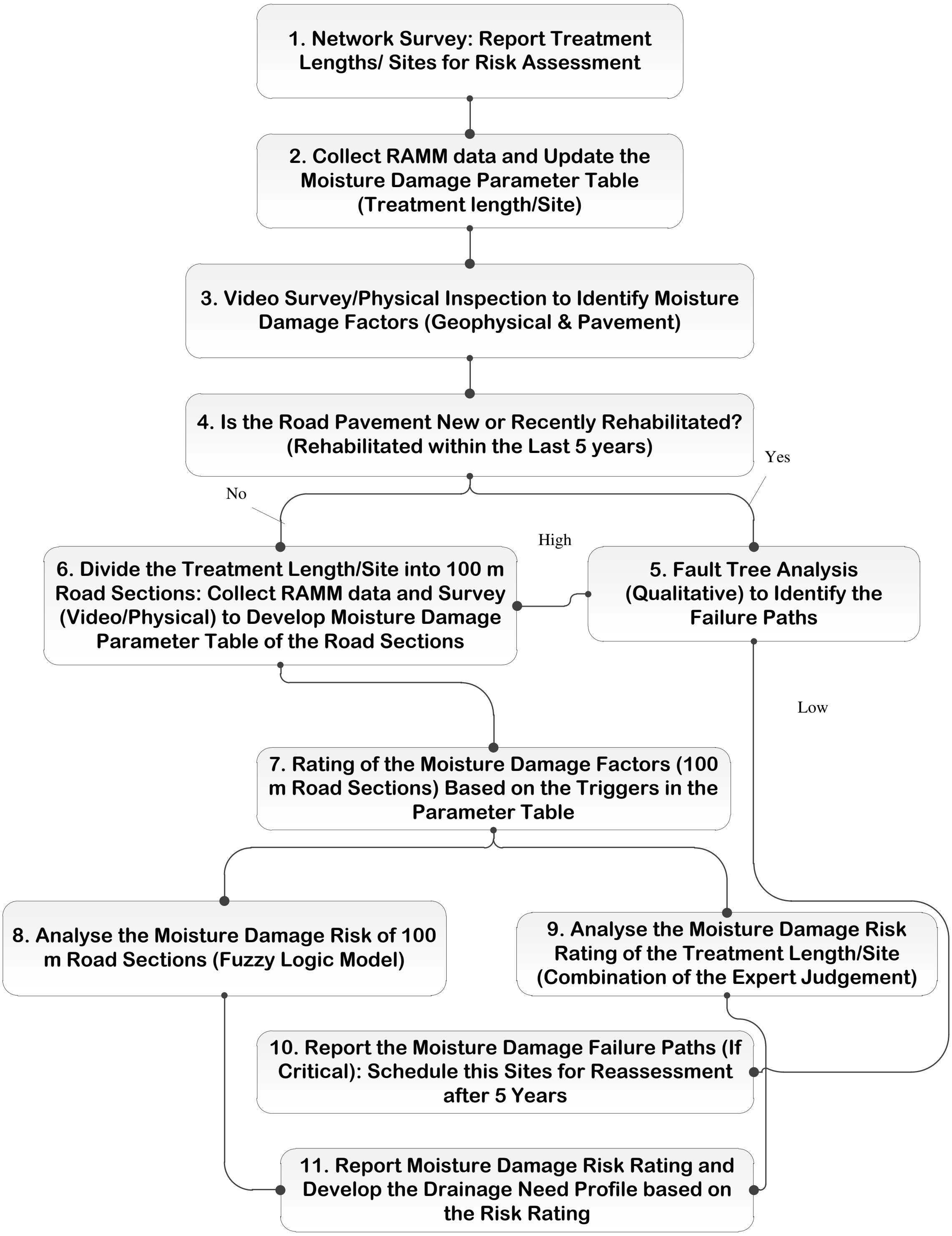


Figure 8-1 Framework of the MDRA (Revised)

The MDRA can be used to predict the risk of premature failure due to the moisture damage of road pavements at early stages of the life cycle. Any road pavement rehabilitated within the last five years or in its first seal cycle is considered as a new road for the purpose of this research. A newly rehabilitated road pavement can be at risk of premature failure, which is categorised as early pavement damage in this research. The symptoms of early pavement damages and their risk assessment procedure are elaborated in the Chapter 5 of the thesis. In New Zealand, the FWP predicts the maintenance need of the road network for the next ten years and the average expected design life of any State Highway road pavement is 25 years. Therefore, The assessment of low risk new road sections has been opted out and are guided for documentation and included in the schedule of drainage improvement (if required) as seen in Figure 8-1.The detailed risk assessment process has to be accomplished in two different stages that are presented in the following sections.

8.2.1 Preliminary Assessment

The preliminary assessment of the road sections is presented by the steps 1 to 6 in the MDRA framework in Figure 8-1. In order to assess the moisture damage risk of any road section, the first step is to extract the pavement and surfacing information out of the road assessment and maintenance management database. The database provides the mass storage of road network information, including the pavement conditions and maintenance expenditure in New Zealand. The road network is frequently surveyed and inspected in order to assess the condition and the level of service. All of the survey and inspection data are used to update the road network maintenance database.

The road network used for this study is composed of a number of treatment lengths/sites developed on the basis of historical maintenance and for the purpose of database management. Usually a treatment length/site is considered as a unit of the road network for collection of pavement parameter databases. During preliminary assessment, the entire treatment length is considered as a unit for risk analysis. Once the location of the road section is confirmed, the information acquired through the database management systems is tabulated based on the moisture damage parameters (Table 8-1). The acquired information helps in identifying the moisture damage parameters that generates triggers for each of the major moisture damage factors. The numbers of triggers for each of the factors help to estimate the risk rating of the moisture damage factors. The data collected from the databases cover most of the parameters in the ‘road classification and pavement-strength’ and the ‘drainage and weather’ risk factors.

In order to collect the geophysical and the pavement profile information, either a physical inspection is required or the use of video surveys. The video survey of the network is robust and usually conducted quarterly in the road network. The video recording files can be used to search for any road section in the network and it can be scrutinised at any speed. The geophysical, pavement characteristics and physical condition of the surface drainage were observed using the video survey data. The subsurface condition of the pavement, especially the pavement strength was evaluated based on the deflection tests on the network. FWD tests were conducted both at the pre and post-rehabilitation of any road pavement. The maximum deflection value is correlated to the pavement layer stiffness and is used as an indicator of the pavement strength in this research (Donovan & Tutumler, 2009). The sub-surface investigation both in the pre and post rehabilitation of a road section, through trenching or coring were logged into the database. These coring data were used to identify the state of the sub-surface drainage, subgrade strength, sensitivity and quality of the pavement materials. Overall, these databases and inspections helped in developing the moisture damage parameter tables at the preliminary stage. Road sections older than five years are recommended for further data collection and to enable a more rigorous risk analysis. A new road pavement is directed for qualitative risk assessment through the FTA as demonstrated in Chapter 5 of the thesis.

The next step in the MDRA is to scrutinise and accumulate additional data based on the initial assessment through FTA. The output of the preliminary assessment (FTA) has to be verified through visual assessment and actual performance of the road pavement. If the FTA does not indicate a possible risk of premature failure, then it is reported as a ‘low risk section’ and scheduled for further review after 5 years. Otherwise the road section has to go through a comprehensive risk analysis as per the MDRA framework (Figure 8-1).

The road section is subdivided into 100 m subsections for risk assessment. Each of the 100 m road sections is then considered as a separate unit and undergoes further scrutiny. The moisture damage parameter table (Table 8-1) is used to develop the trigger based database of the 100 m road sections. The 100 m road section is a standard unit for risk assessment and has been adopted by the NZTA as the preferred treatment length for its prioritisation study (NZTA, 2014). The data collection strategy presented earlier was followed to accumulate the moisture damage parameters from the database of the subdivided 100 m road sections. This data accumulation is to develop the database which has been used for further risk assessment in the final stage. Validation is vital at this stage of risk analysis because each of the major moisture damage factors (Table 8-1) of these subdivided road sections had to be evaluated based on the estimated triggers and subjective judgment of the expert.

8.2.2 Final Risk Analysis and Reporting

Once the 100 m road sections moisture damage parameter table is updated, the next step is to conduct the risk analysis through the MDRA framework (Steps 7 to 11 in Figure 8-1). It is perceived to apply both the 'fuzzy logic model' and the 'combination of the moisture damage factors' techniques for risk analysis at this stage. Initially, they were considered as candidate risk analysis techniques in MDRA, but later on both of them were adopted for risk analysis. The fuzzy logic model is essential in identifying the risks of individual 100 m road sections, whereas, the combined distribution technique can provide the risk rating of the treatment length.

The risk analysis technique was developed in the Matlab environment and incorporates expert judgment in risk assessment. Figure 8-4 shows the structure of the model. The model consists of four inputs or moisture damage factors, inference rules and the output i.e. Moisture Damage Risk Rating. The 'geophysical' and the 'pavement and shoulder' are two static factors and the 'Road Class & Strength' along with 'Drainage', are the dynamic factors in the model. The static factors are defined by *two* trapezoidal membership functions such as 'Low' and 'High'. Whereas, the dynamic moisture damage factors are defined by three trapezoidal membership functions (Low, High and Very High). These trapezoidal membership functions had been used in a number of research studies of risk assessment (Rezakhani, 2012; Zlateva et al., 2011).

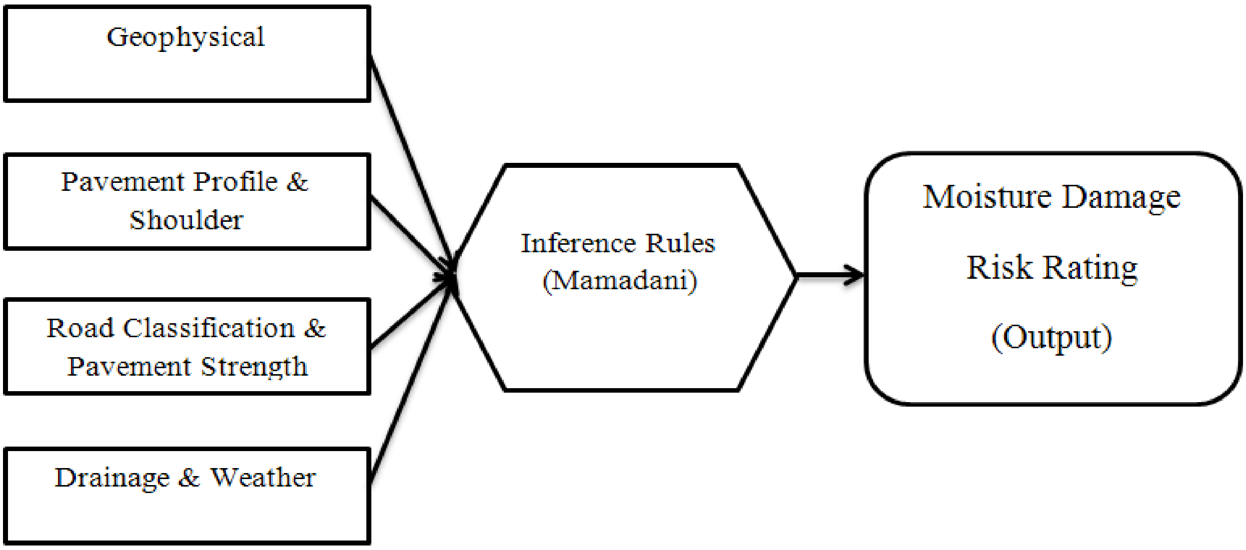


Figure 8-2 Structure of the Risk Analysis Model (Fuzzy Logic)

A total of 26 "If-Then" based inference rules were used in the model based on expert judgment (Appendix B). The inference rules are simulated in the rule viewer output in Figure 8-3. This rule viewer tool is used to assess the road sections based on the input moisture damage factors. In Figure 8-3, four moisture damage factors (8.63, 8.39, 8.87 and 8.98) yielded a moisture damage risk rating of 9.0 based on the inference rules. The ratings of the moisture damage factors can be changed manually in the rule viewer to generate the moisture damage risk rating of any road section. The ratings of the moisture damage factors are derived from the database developed, based on the moisture damage parameter table (Table 8-1).

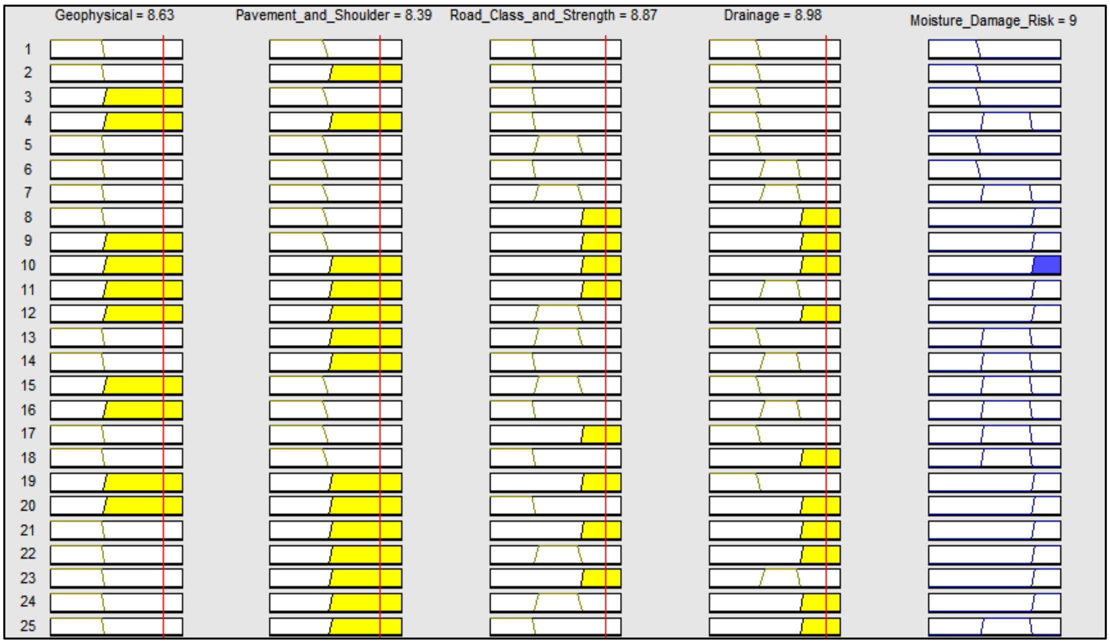
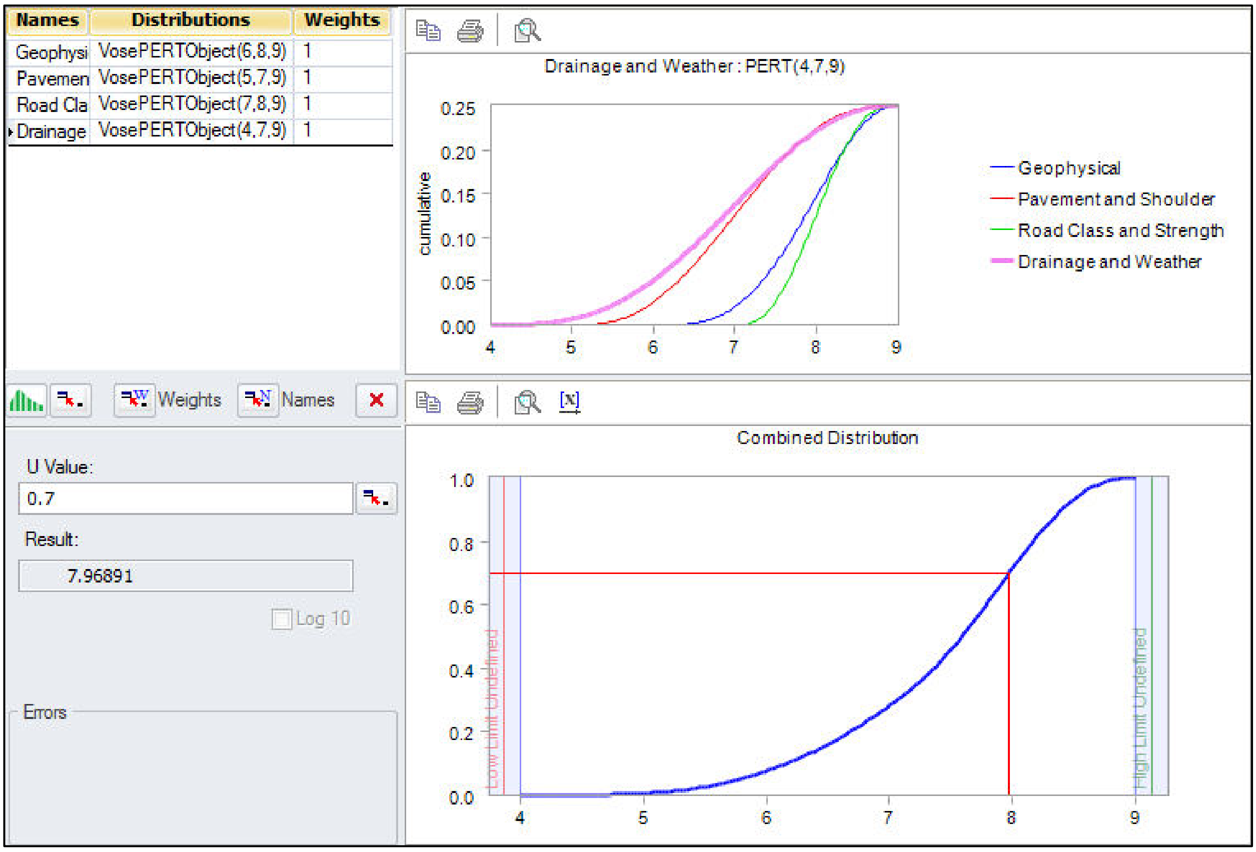


Figure 8-3 Rule Viewer of the Risk Analysis Model (Fuzzy Logic)

'Combined distribution of moisture damage factors' has been used to identify the overall risk rating of the treatment length based on risk assessment of the 100 m road sections. The model was developed using the Microsoft Excel add-in "Model Risk" developed by Vose Software. The combined-Distribution model was used to identify the moisture damage risk rating of the treatment length. The moisture damage risk factors of the ten road sections (100 m) generated the four distribution curves in the top box (Figure 8-4). These curves were combined to yield the resultant curve (in lower box) which represents the combined moisture damage risk of the treatment length. The cumulative distribution curve can then be used to identify the rating based on any percentile value. Here the U value in Figure 8-4, indicates the 70th percentile of the distribution curve and the concerned horizontal axis (X=7.97) value is perceived as the moisture damage risk rating of the treatment length.



Names	Distributions	Weights
Geophysi	VosePERTObject(6,8,9)	1
Pavemen	VosePERTObject(5,7,9)	1
Road Cla	VosePERTObject(7,8,9)	1
Drainage	VosePERTObject(4,7,9)	1

U Value: 0.7

Result: 7.96891

☐ Log 10

Errors

Figure 8-4 MDRA Risk Rating (70th Percentile) of the Road Section

The 70th percentile value was considered to provide the combined risk rating of the treatment length based on the moisture damage factors of the road sections (100 m). This indicates that the combined risk rating of the treatment length includes more than two-thirds of the risk rating of the 100 m road sections. Road controlling authorities may select any value from the range of 50th to 90th percentile based on the experiences of the road network.

The next step is to evaluate the MDRA through correlating the actual performances of the road section. The road sections were monitored for rutting, roughness (NAASRA) and cracking (rating) during the research period. These pavement condition parameters will be used to assess the actual performance of the road sections. The trend of these pavement condition parameters indicates about the vulnerability of the road sections that will be used to correlate the predicted risk of the MDRA. The performance of the road section can be reflected from its maintenance cost trend. As the maintenance of a road section is to repair the pavement distresses, so the cost trend indirectly reflects the performances of the road pavement as well. Therefore, the maintenance cost trend of the road sections was used to evaluate the predicted risk of the MDRA.

8.3 Evaluation of the MDRA

The purpose of this section is to evaluate the risk assessment framework (MDRA) based on its performance and long-term application in drainage risk assessment. The application of MDRA in moisture damage risk assessment mostly depends on its success in identifying the road sections where drainage improvement is essential. Therefore, it is vital to verify the performance of the MDRA in predicting the moisture damage risk of the road section. Here the critical part is to set up the criteria to evaluate the MDRA. In this respect, three fundamental components of road network management were considered as the platform for the required evaluation of the MDRA. The concepts of 'Condition Monitoring', 'Life Cycle Cost' and the 'Forward Work Programme', were used to evaluate the application of MDRA in road asset management.

The MDRA can be utilised at different stages of the road network maintenance cycle, such as the planning stage of the pavement and drainage renewals. An overall Forward Works Programme (FWP) for the network is developed on the basis of multi decision tools and processes. The FWP includes the current and future pavement and drainage renewal and resurfacing works based on current asset condition and deterioration modelling (NZTA, 2014). In New Zealand, the road controlling authorities utilise the deterioration modelling software for developing the FWP and to prioritise the planned treatment works. This model is recognised for its capability in predicting and optimising the maintenance treatment selection and in generating the forward works programmes (Henning et al., 2006). The road sections from the modelling output are expected to include the rehabilitation work that yields the best life cycle performance and least maintenance cost (NZTA, 2014). The MDRA can be used to predict the moisture damage risks of the road sections and the risk ratings can be used in developing the forward work programmes, especially for the drainage renewals.

The road section has been subdivided into a number of treatment lengths of variable length. This treatment length is used for analysis for deterioration modelling that generates the FWP of the road section. The MDRA gives the status of the risk of a road section, whereas the forward work programme indicates the priority of that road section. Usually, the most vulnerable road sections that are at the end of the life cycle are selected for rehabilitation within the next five years. In addition, the road sections selected for resealing are also at high risk and required the preservation treatment to increase the life cycle. In particular the resealing of the road section will make the surfacing waterproof which eventually increases the integrity of the road pavement (Austroads, 2008b). The comparison of the moisture damage risk

(MDRA) and the treatment in the FWP may indicate the performance of the MDRA. The methodology to evaluate the MDRA was proposed in Mia et al. (2013). In the course of time during the development of MDRA, the evaluation methodology was further developed to identify the correlation between the risk assessment and the actual performance of the road section. In order to assess the performance of the MDRA, a case study has been conducted in the road network under study. A 15 km road section of the network has been used in the case study. The MDRA is used to assess the moisture damage risk of the road sections. Then the outcome of the risk assessment has been correlated with the forward works programme.

8.3.1 Condition Monitoring

The short and long term monitoring of the road pavement condition is a key performance assessment in road network management. The objective of the condition monitoring is to assess the level of service of the road network, especially in performance based maintenance contracts (Daly, 2004). In this case, the network management organisation has to report the monitoring and inspection of road network assets. These include the pavement distresses monitoring such as rutting, roughness, shoving, potholes, high/low shoulder, edge-break and disintegration of the shoulder. There is a number of condition monitoring strategies adopted by the road controlling authorities based on the specific requirements. The Table 8-2 summarises different monitoring and inspection strategies of New Zealand road controlling authorities.

Table 8-2 Condition Monitoring Strategies

Monitoring Strategy	Purpose of the Condition Monitoring
Long Term Pavement Performance (LTPP) Programme	This long term pavement performance monitoring was adopted in 2000 in New Zealand. The programme includes annual monitoring of pavement distresses such as rutting, roughness, texture, cracking and FWD testing of candidate road sections over the country. There are 83 road sections (300 m length) on national State Highways, selected for long term monitoring in the programme. These road sections are selected to cover the wide range of climatic conditions, traffic volumes, pavement strength, age, conditions and subgrade material. The objective of the LTPP monitoring is to create a database of candidate sites. This database has been utilised in formulating and calibrating the deterioration model used to identify the long-term maintenance requirements of road networks in New Zealand (Henning et al., 2004; Henning et al., 2006).
Annual high speed data road survey and condition monitoring	The annual monitoring of pavement and surface condition is vital for New Zealand road network (NZTA, 2016). Usually the high-speed condition survey is done by the (Sideway-force Coefficient Routine Investigation Machine) SCRIM+ vehicle between October and February. The high speed condition monitoring includes but is not limited to the measurement of the following parameters;

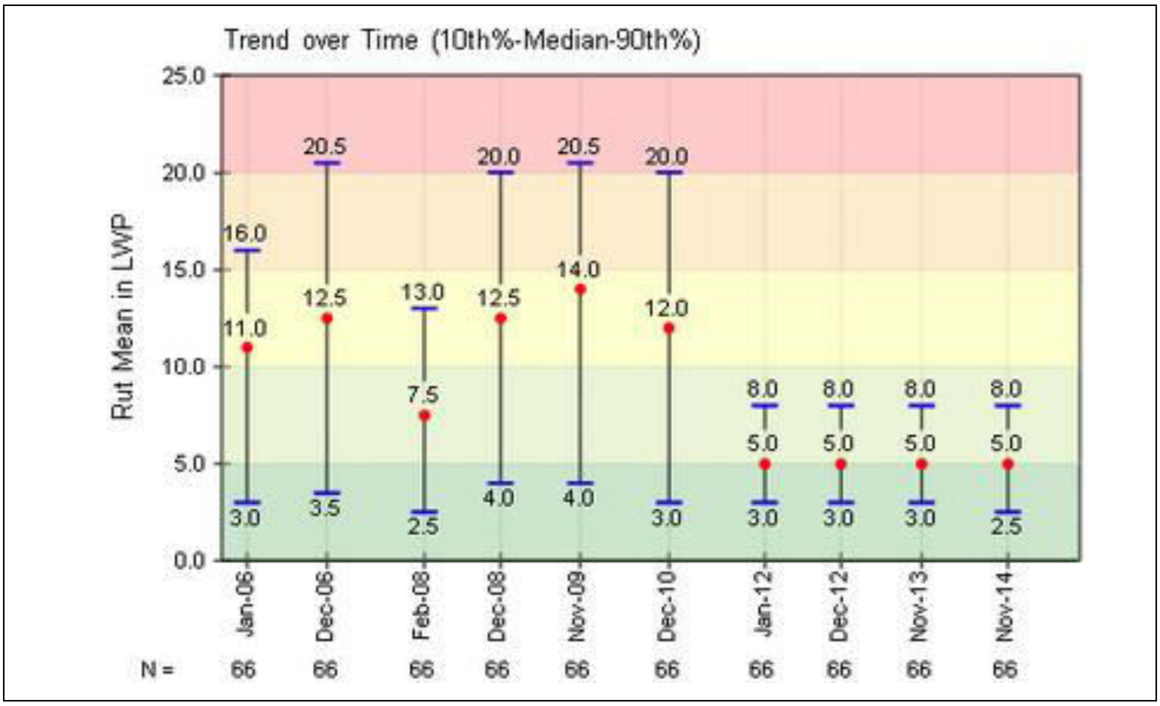
Monitoring Strategy	Purpose of the Condition Monitoring
	• Transverse profile (These data are used to determine the average, maximum and minimum rut depth; the wheel path rutting is simulated based on the data as well); • Longitudinal profile (Roughness are calculated from the longitudinal profile and reported in every 20 m); • Texture of the road pavement in mean profile depth; • Skid resistance of continuous 10 m road sections; • In addition, the road geometry (horizontal and vertical curvature) and the network video at high speed (80 Km/h). These high speed data surveys are conducted for monitoring the performance and condition trends of the highways, for planning of future maintenance work and also to predict the future condition of the road network based on deterioration modelling (NZTA, 2016).
Frequent Audit and Inspection of Road network Assets	Frequent audit and inspection is a vital part of the road network maintenance. In both the performance-based and the NOC models, the road network assets (pavement, drainage, guardrails, bridges, various traffic and warning signs) have to be regularly inspected and reported to evaluate the performance of the contracts. The pavement distresses like rutting, roughness, cracking, potholes, shoves, heaves, edge-break, high & low shoulder have to be counted and repaired to ensure the performance of the road network. Usually the level of performance is measured against the prescribed key performance indicator and key result areas (NZTA, 2014).

The maintenance and management of this asset condition database is a vital part of road network management. An extensive database can provide vital information about the network condition assessment, for both short and long-term planning, prioritisation of maintenance and improvement works. The road pavement condition and distress data can be used for assessment of the risk of the road section. It is the responsibility of both the road controlling authorities and the network management organisation to maintain and update the network asset condition database. The management organisation is responsible for collecting and updating changes in geometric and pavement features into the database due to the road network improvement works. This road condition database can be an essential part of the desired evaluation process of the MDRA.

The road network condition can indicate its risk status in respect of structural condition and the level of service. The level of rutting and roughness indicate whether a road pavement is at risk in term of failure or the poor level of service. However, the key factor is the level of increment of these pavement distresses that essentially signifies whether a pavement reaches its terminal stages. Figure 8-5 gives the trends of left wheel path rutting and roughness

(NAASRA) of a road section. The database developed for the management organisations acquired the condition data from the road asset maintenance and management database and utilise them for reporting purposes (NZTA, 2005).

The top curve in Figure 8-5 shows the left wheel path rutting trend since 2006. This trend is based on the high speed data survey conducted by the NZTA, usually in summer in New Zealand. The trend line for each year indicates the 10th percentile, median and 90th percentile value of the road section. The key indicator of this trend is the progression of rutting. It can be observed that, there is a sharp increase in rutting between January and December 2006. The level of rutting crossed the maximum tolerable limit and eventually the site was repaired (stabilization patching) which can be noted by the reduction of rutting between 2006 and 2008. However, the progression of rutting continues and increases abruptly from 2008 to 2010. The level of rutting reached the critical stage in 2010 and indicated the end of the life cycle. The site was rehabilitated with major drainage renewal in 2011. This resulted in the resetting of rutting on January 2012. Since then the site has shown a relatively constant increase in rutting from 2012 to 2014.



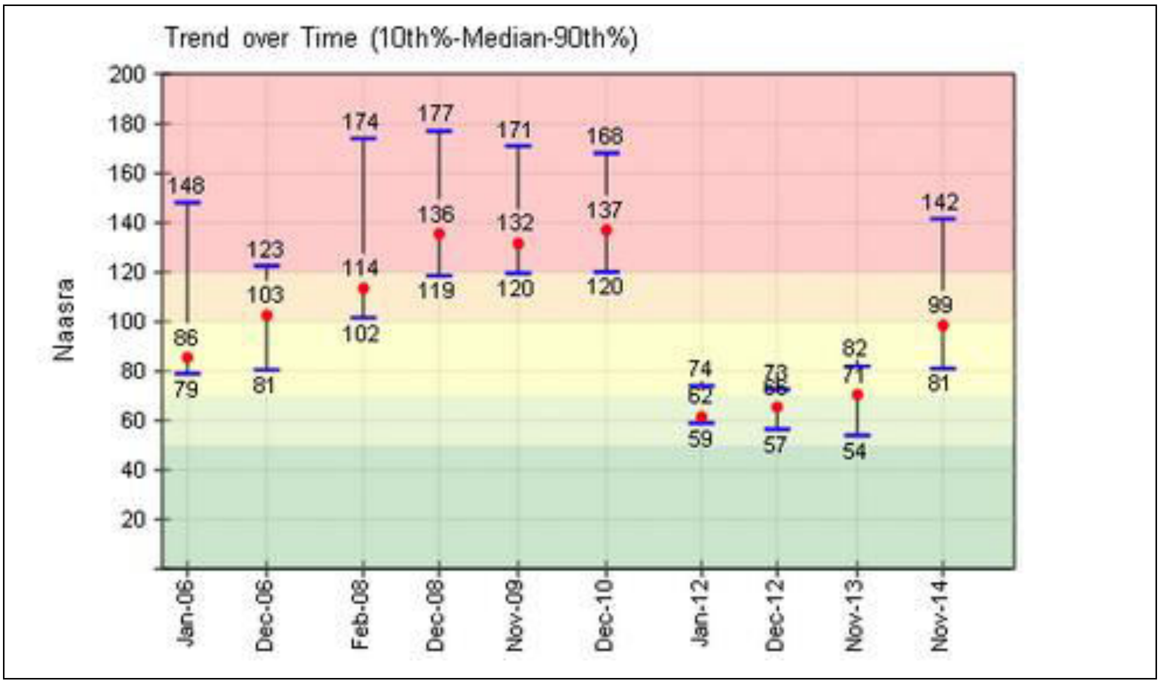


Figure 8-5 Trend of Rutting (Left wheel path) and Roughness (NAASRA)

A similar trend is observed for progression of roughness trend lines from 2006 to 2010. The roughness reached its terminal stages in 2010 and essentially rehabilitated in 2011. The roughness value was reset in 2012 and since then it has been stable up to November 2013. The sharp increase in roughness value is observed between 2013 and 2014 (Figure 8-5). The rutting and roughness trend of the site observed in Figure 8-5 indicates the site is at high risk of moisture damage. The trend lines indicate the site may have historical problems of moisture damages. From 2006 to 2010 both trends of rutting and roughness indicate that the pavement was at high risk of structural failure and poor level of service due to surface failure. However, the risk of structural failure seems to be reduced based on the rutting trend after the rehabilitation of pavement in 2011. This might be due to drainage improvement which essentially reduces the risk of sub-surface failure. However, the poor performance due to an increase in roughness still continues, which indicates the possibility of potholes, stripping, heaving and shoving due to frequent surface flooding in those areas. The evaluation of MDRA can be conducted through the correlation between the predicted risk rating of a road section and the actual performance or the condition trend.

8.3.2 Life Cycle Cost (Maintenance)

The cost of maintenance of a road pavement at different stages of life cycle indicates about the integrity of the road pavement. A number of external factors such as climate, precipitation, subgrade condition, pavement material and construction quality, affect the maintenance cost of a road pavement. A life cycle cost (maintenance) model was developed based on the actual maintenance cost of a number of road sections. The historical maintenance costs of the road sections are calculated as the cost per kilometre of road section. Then the cost of the road sections is averaged and accumulated to plot the cost models in Figure 8-6. The horizontal axis shows the life cycle of the road pavement.

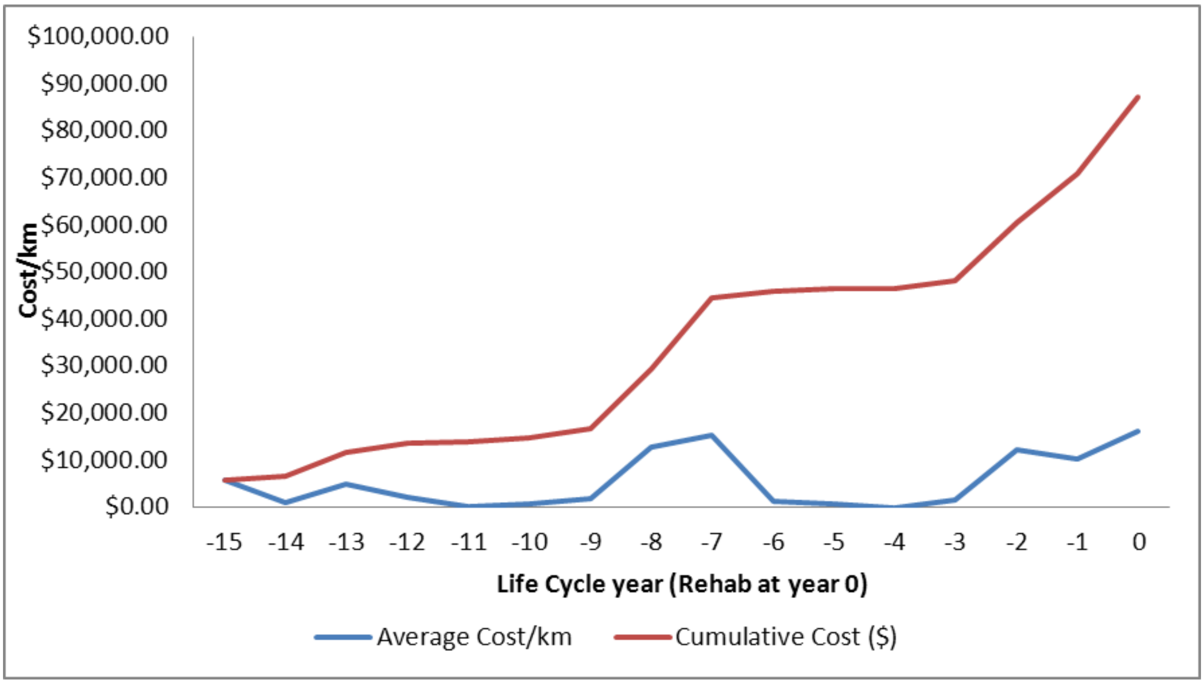


Figure 8-6 Life Cycle Cost (Maintenance) of a Road Network

Here the year 0 is conceptualised as the end of the life cycle or close to a major repair or rehabilitation. The vertical axis shows the maintenance cost per kilometre (average) of several road sections. The cost model is for the road sections that are close to structural or pavement failure. The predominant distresses in these road sections are rutting, roughness, shoving, depressions, heaves, and widespread cracking. The beginning of the cost model (average cost/km) does not necessarily indicate the beginning of the life cycle. Rather, it is the end of the minor maintenance period. The first two peaks at years (-13 and -7) indicate two major repair works in the life cycle. There is another low maintenance cost period from the year (-6) to (-3), and then the maintenance cost started increasing and eventually reaches a stage (year 0) when it requires either major repair or rehabilitation. The road pavements usually are at critical stages at year 0 and can be considered at risk of failure. Thus the life cycle maintenance cost curve can be used to identify the vulnerability of the road section.

8.3.3 Forward Work Programme (FWP)

The FWP is the output of the long-term planning and prioritisation of the maintenance activities in a road network. Usually, the FWP is developed based on the deterioration modelling of a road network. In New Zealand, the deterioration modelling is used to analyse the road network to identify the optimum maintenance needs in order to maintain the level of service (Henning et al., 2006). The network is divided into a number of treatment sites (variable) that are being used as the units for the deterioration analysis. There are different ways to run the deterioration modelling of a road network. It involves the fixed or predetermined maintenance budget as one of the inputs. The empirical modelling involves prediction of future pavement distresses based on the current failure trend. The modelling output should be a long-term distribution of the network preservation activities such as rehabilitation, resealing and asphalt resurfacing, required for maintaining the level of service. The sites identified through the modelling have to be verified to correlate the output of the modelling with the actual pavement condition. Once the expert verifies the deterioration modelling output, this will be the basis to develop the FWP of the road network. Another way is to develop the FWP based on the inspection, laboratory & field test data and condition monitoring. This specified FWP need to be uploaded along with the specified budget. The objective is to identify whether the predicted FWP is compatible with the budget and meet the requirement of the road network to ensure the level of service. Overall, the objective of both the deterioration-modelling techniques is to develop the FWP, which will be the basis for future maintenance need of the road network.

The FWP can be developed for a number of durations. However, the 3, 10 and 30 year FWP's are more familiar in New Zealand. The FWP can be demonstrated in different formats. The key is to provide the fundamental properties of a treatment length along with the projected treatment (maintenance) within the analysis period. Table 8-3 shows an example of a 10 year, FWP developed for the four different sites in a road network.

Table 8-3 Example of a 10 year FWP

Site	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Year 7**	**Year 8**	**Year 9**	**Year 10**
A				RHAB	SC					
B							RS			
C	RS								RS	
D		RHAB	SC							
E										

Note: RHAB: Rehabilitation of Pavement; SC: Second coat; RS: Resurfacing of pavement (chip seal)

The FWP in Table 8-3 indicates that sites A and D reach their end of life cycle and need to be rehabilitated within the next five years. Site C is programmed for resurfacing next year, which will reduce the level of risk of failure. On the other hand, the site can be considered at low risk; consequently no treatment is required based on the deterioration modelling within the next ten years. Thus, the FWP can be used as a potential framework to compare the performance of MDRA in predicting road sections at moisture damage risk.

8.4 Evaluation of the MDRA (Application) Based on FWP

The case study involves the risk assessment of the 15 km road section in the road network. The location of the road section is shown in Figure 8-7. The road section was divided into 38 treatment lengths/sites of varying length. Table 8-4 provides the length, width, pavement layer date (the date of latest rehabilitation) and programmed treatment based on the FWP of the network.

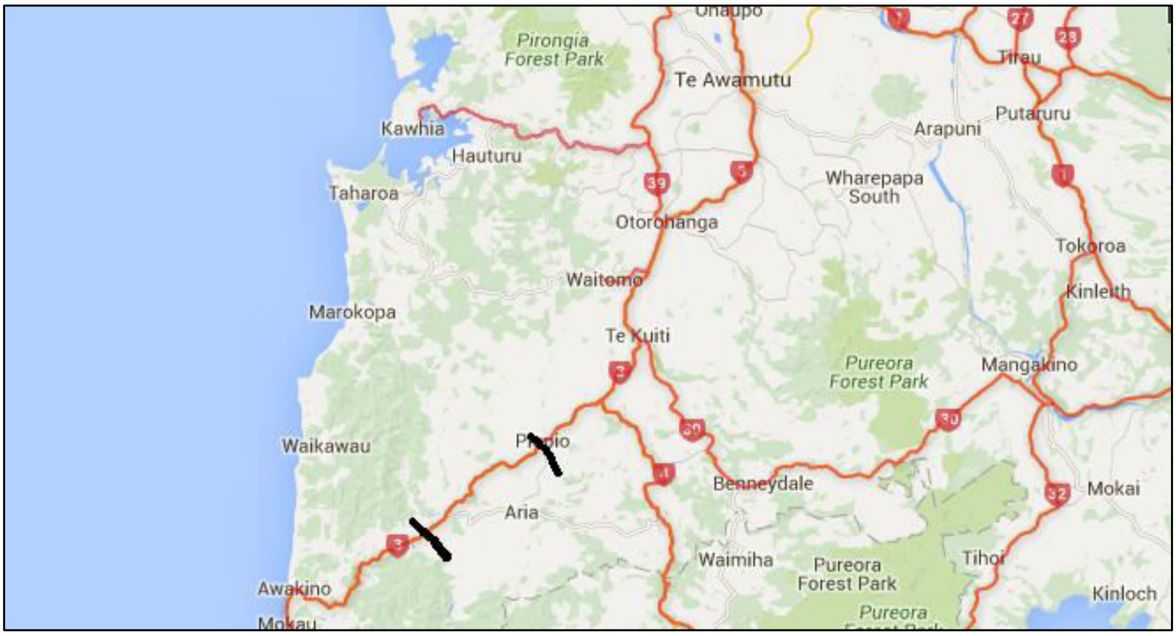


Figure 8-7 Location of the Road Section in a State Highway Selected for case Study

Table 8-4 Treatment Lengths of the Road Section

Treatment Length/Site	Length (m)	Width (m)	Pavement Date	Programmed Treatment	Year	Priority of Road Section (FWP)	No. of 100 m sections
T 001	570	11.1	25/12/1982	RS	2022	High	6
T 002	299	9.2	09/02/2014	RS	2022	High	3
T 003	309	8.8	01/04/1999	RS	2028		3
T 004	723	8.8	25/12/1983	RHAB/RS	2018/ 2019	Very High	7
T 005	187	8.8	05/02/2005	RHAB/RS	2027/2028		2
T 006	256	8.8	25/12/1983	RS	2018	Very High	3
T 007	387	8.8	19/10/2006	RS	2020	Very High	4

Treatment Length/Site	Length (m)	Width (m)	Pavement Date	Programmed Treatment	Year	Priority of Road Section (FWP)	No. of 100 m sections
T 008	674	8.97	25/12/1983	RHAB	2020	Very High	7
T 009	355	9.3	23/11/2002	RS	2025	High	4
T 010	351	9.3	23/11/2002	RS	2025	High	4
T 011	549	9.3	23/11/2002	RS	2026		6
T 012	220	9.3	20/03/1998	RS	2024	High	2
T 013	790	9.3	05/06/2005	RHAB/RS	2028/29		8
T 014	125	9.3	25/12/1984	RS	2017	Very High	1
T 015	462	9.22	19/11/2005	RHAB/RS	2028/2029		5
T 016	600	8	25/02/2000	RS	2023	High	6
T 017	288	8	05/10/2007	RHAB/RS	2020/2021	Very High	3
T 018	281	8	06/08/2003	RS	2023	High	3
T 019	555	8	06/08/2003	RS	2024	High	6
T 020	619	8	06/08/2003	RS	2022	High	6
T 021	565	8	06/08/2003	RS	2017	Very High	6
T 022	225	8	11/4/2007	RHAB/RS	2024/2025	High	2
T 023	87	8	11/4/2007	TAC	2024	High	1
T 024	708	8	11/4/2007	RS	2016	Very High	7
T 025	165	8	02/05/2001	RHAB/RS	2022/23	High	2
T 026	260	8	25/12/1984	RHAB./RS	2022/23	High	3
T 027	157	8	02/05/2001	RHAB/RS	2022/23	High	2
T 028	128	8	18/4/2007	RS	2018	Very High	1
T 029	133	8	18/4/2007	RS	2017	Very High	1
T 030	162	8	18/4/2007	RS	2020	High	2
T 031	310	8	02/05/2001	RS	2028		3
T 032	674	8	02/05/2001	RS	2016	Very High	7
T 033	371	8.4	25/12/1984	RHAB/RS	2019/2020	Very High	4
T 034	445	8	25/12/1984	RHAB/RS	2019/2020	Very High	5
T 035	150	8	25/12/1984	TAC	2025		2
T 036	628	8	02/03/2002	RS	2019	Very High	6
T 037	512	12.28	12/06/2007	RS	2016	Very High	5
T 038	266	8.4	25/12/1982	RS	2027		3
Total	14546						151

In order to assess the moisture damage risk of the sites, they were subdivided into 100 m road sections. The 100 m road sections are the smallest unit used for risk assessment through MDRA. As per the framework of the MDRA, these 100 m road sections were analysed through the fuzzy logic model. The vulnerability of the road sections was assumed based on the programmed treatment in the FWP. The road sections programmed for treatment within the next 5 years are considered to be at risk of failure. Whereas, the road sections requiring treatment after 10 years can be considered for treatment in the course of the life cycle.

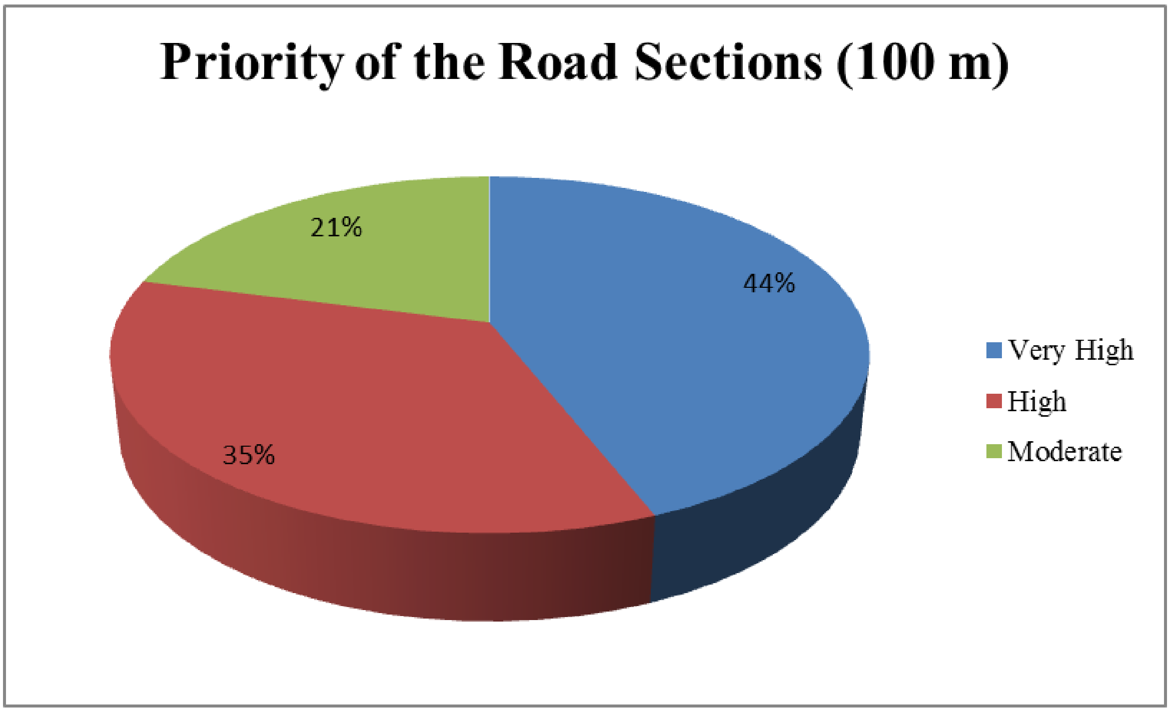


Figure 8-8 Road Sections Priority based on the FWP[2]

Figure 8-8 shows the distribution of the 100 m road sections based on their priorities in the FWP. The sites with higher priority are defined as ‘Very High’ and have been programmed for any major treatment (Rehabilitation and Resealing) with the next 5 years. The road sections that are on ‘High’ priority have been programmed for any major treatment within 5 to 10 years. Road sections that have not been included in any treatment in the FWP are considered as ‘moderate’ for this evaluation purpose. In respect to the FWP of the 15 km site, almost half of the road sections are at very high risk and successively selected for either rehabilitation or resurfacing within the next five years. Approximately two-thirds of the road sections are of ‘high’ or ‘very high’ risk in respect of the programmed treatment in the FWP. The road sections (100 m) in Table 8-2 were analysed for moisture damage risk using the updated MDRA framework.

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[2] Note: Very High (Sites need preservation within the next 5 years); High (Preservation within 5-10 years) and Moderate (Rest of the road section programmed for treatment after 10 years)

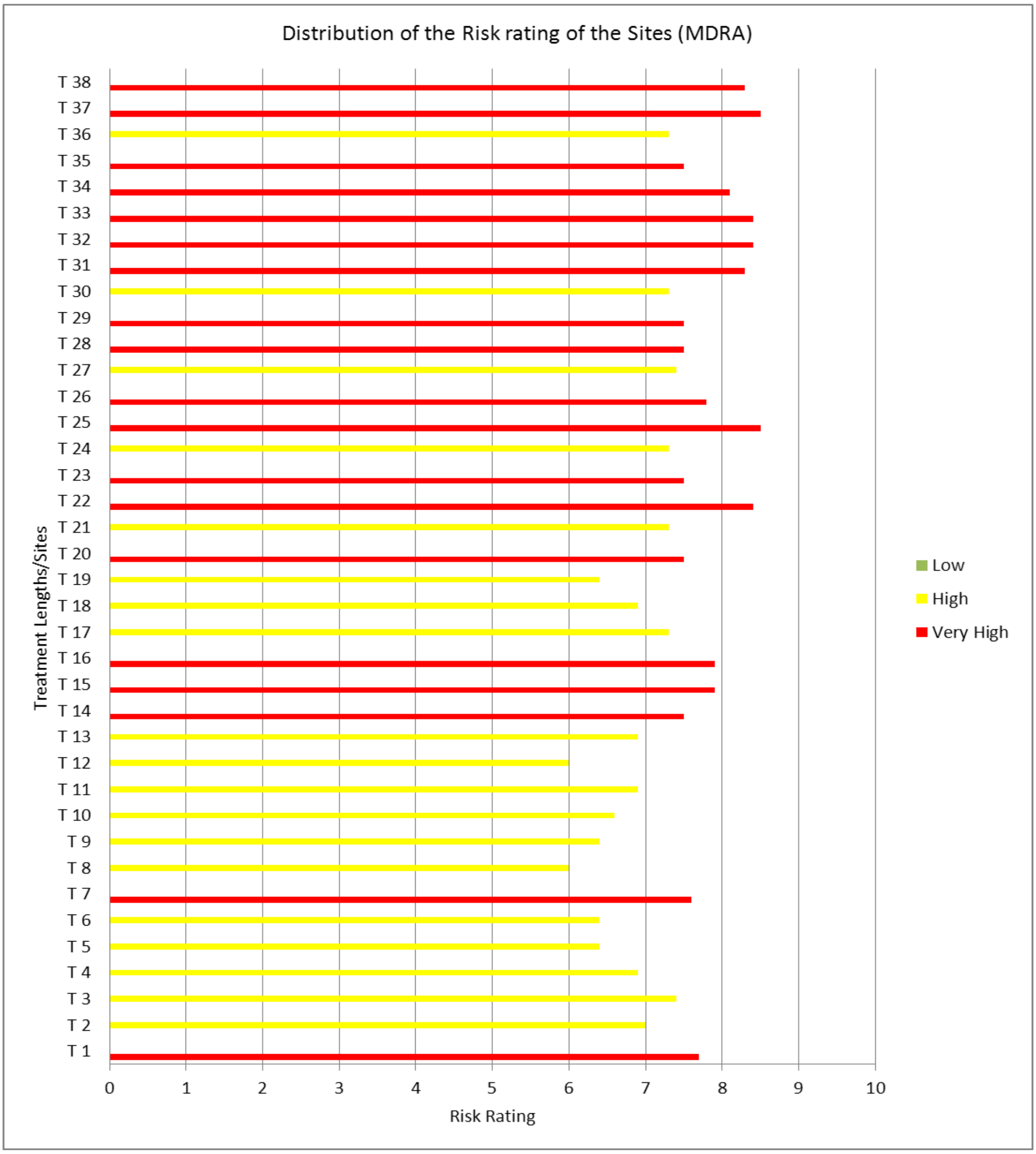


Figure 8-9 Combined Risk Rating of the TLs Based on MDRA

Figure 8-9 shows the longitudinal distribution of the moisture damage risk rating of the 38 treatment sites/lengths of the 15 km road section. Based on the risk rating distribution, none of the road sections is at low risk. Any site over the risk rating of 7.5 is considered at 'Very High' as per the MDRA output membership function. These sites are represented by red bars in the distribution chart in Figure 8-9. The risk rating in the range of 6 to 7.5 is considered to be as 'High' and roughly around 40% of the sites are in this group. The risk rating of each treatment length is the combination of the ratings of the 100 m road sections (Figure 8-10) within the treatment length. The distribution gives a platform to compare with the actual pavement condition and the vulnerability (FWP) of the road section. The first half (T 001 to T 019) of the road sample are mostly of 'High' risk road sections. The latter halves of the sample are found to be at 'Very High' risk of failure due to moisture damage. Figure 8-10 shows the distribution of the risk ratings of 100 m road sections in the 15 km length of road.

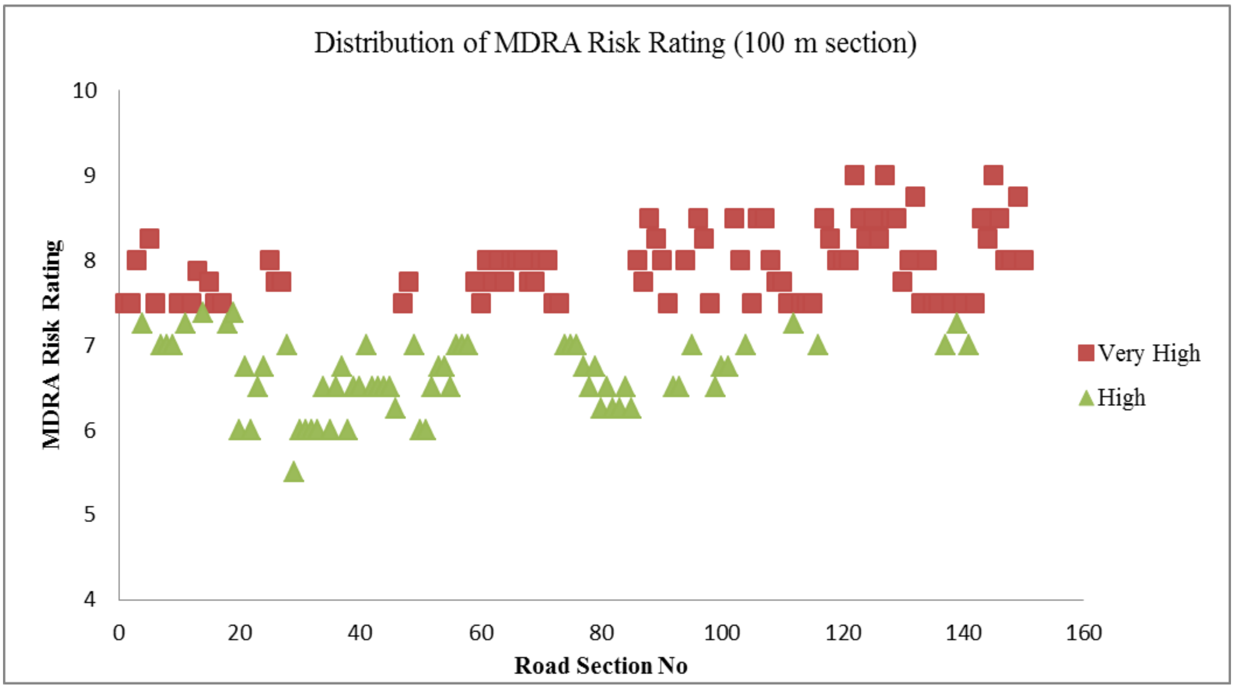


Figure 8-10 Distribution of MDRA Risk Rating

In order to comment on the effectiveness of the MDRA, the comparative prioritisation of the two different prediction frameworks (FWP and MDRA) is presented in Figure 8-11. The FWP of the road sections indicates that almost 44% of them are most at risk of failure and need to be rehabilitated or repaired within the next five years. The MDRA predicts roughly around 55% of the road section to be at very high risk, including those sections indicated by the FWP. The MDRA indicates that almost 42% of the road sections are at 'High" risk that includes the 35% of the road section predicted to be repaired within the next 5 to 10 years. The MDRA predicted only 2% of the road network as 'Low' risk which is comparable to the 20% of the road sections predicted by the FWP to sustain for more than 10 years. This is fairly reasonable because the FWP is developed based on the deterioration modelling which essentially considers a number of factors, including the pavement distresses due to excess moisture in road pavement. An in-depth analysis of each individual road section would give a better understanding of the prediction capabilities of the two frameworks (FWP and MDRA).

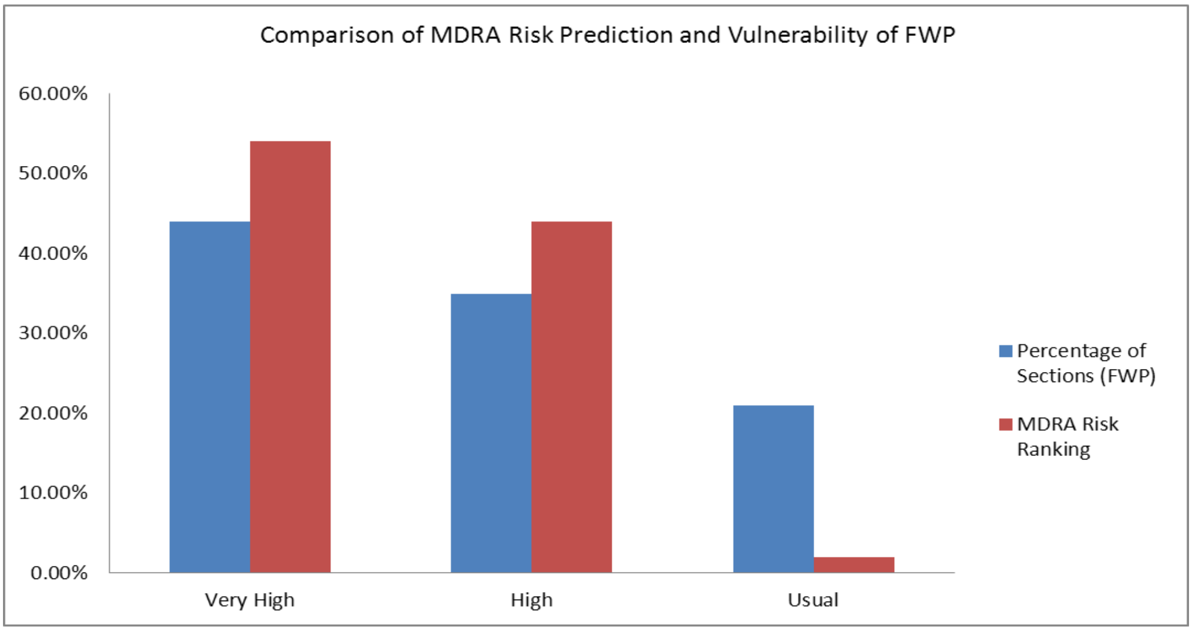
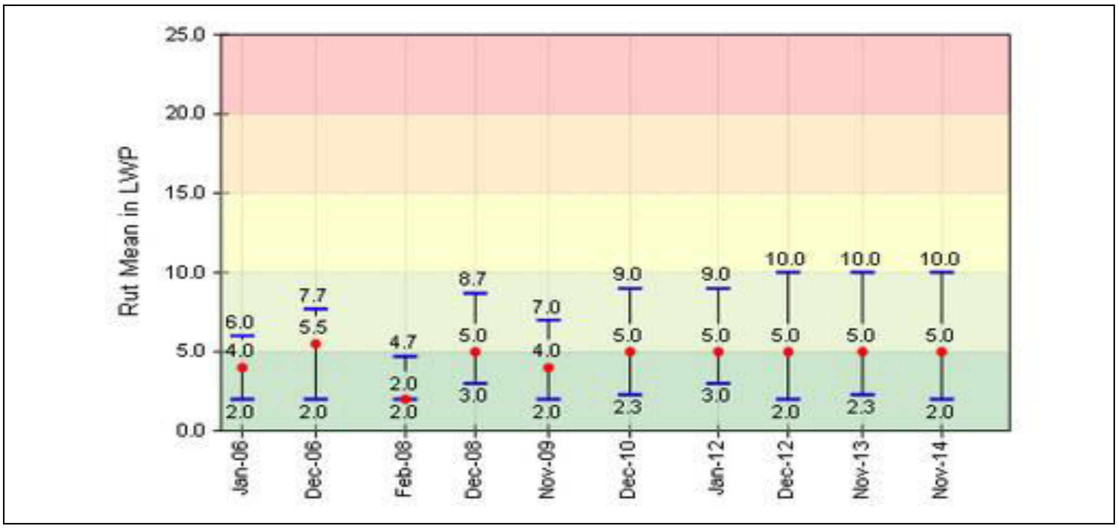


Figure 8-11 Distribution of Road Sections Based on the Two Framework (FWP and MDRA)

8.4.1 Case Studies for Evaluation of the MDRA

In order to evaluate the performance of MDRA, an in-depth analysis of the condition trend, maintenance cost pattern and road pavement performance of different sites was conducted. The objective is to identify the correlation between the predicted risk rating of MDRA and the actual performances of any road section.

1. **Site T 037 (Unsound Pavement):** This site was rehabilitated in 2007-08 and programmed for resealing in 2016-17.



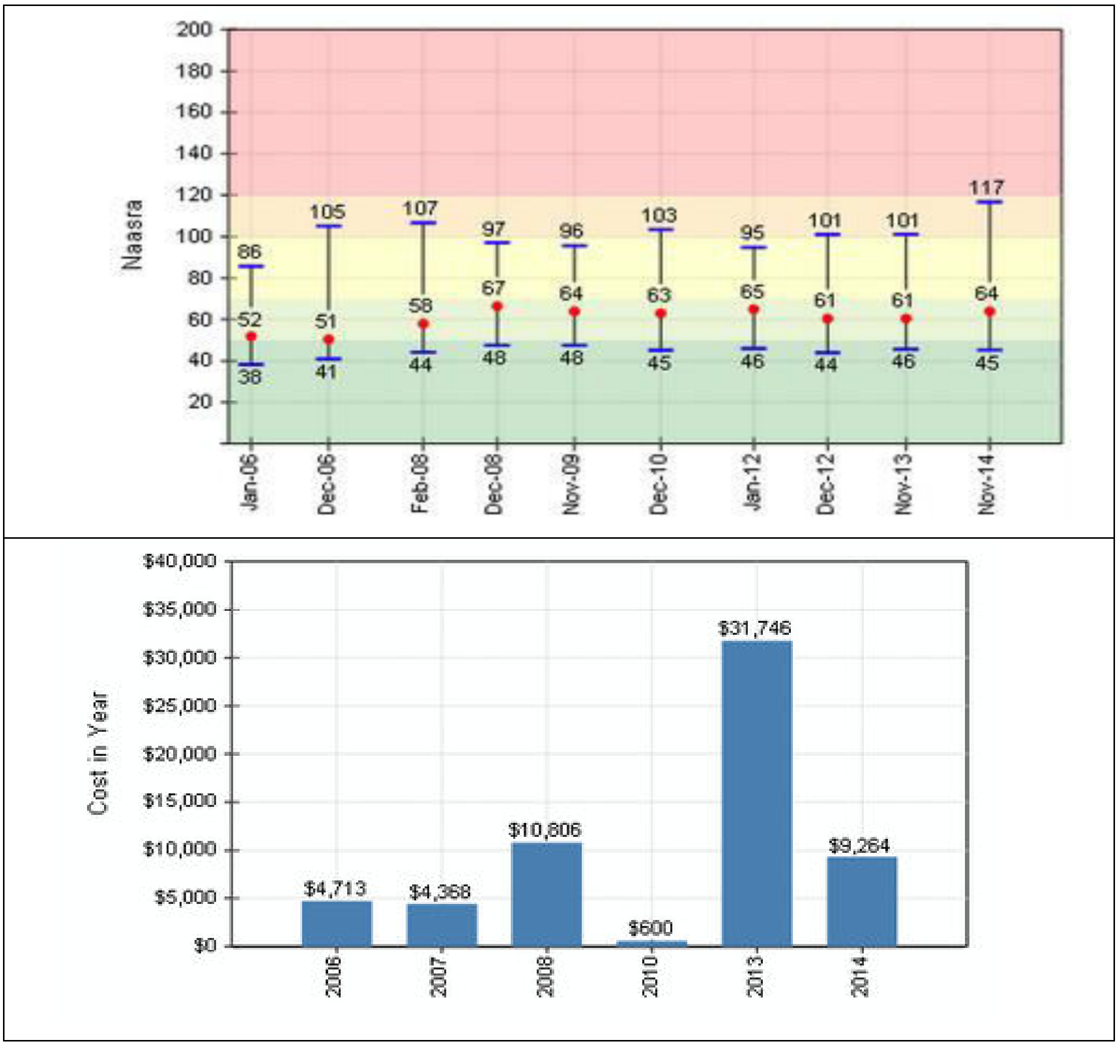


Figure 8-12 Pavement Condition (Rutting and Roughness) and Maintenance Cost

The pavement condition trends (Figure 8-12) indicate that the pavement is structurally unsound. The average left wheel path rutting of the road section has been steady since 2010. In addition, the roughness trend of the road section is also steady. The average NAASRA remains constant for the last four years, however, the 90th percentile of the roughness value increases significantly over the last year. The maintenance cost trend in Figure 8-12, indicates that the road section is actually at risk of failure. The average maintenance cost of the road section over the last two years is roughly around $20,000.00. The major problems identified during the field inspection were flushing, stripping, potholes, edge-break and localised stabilisation patches. All of these have contributed to the high maintenance cost and increase in roughness over the last two years. The MDRA risk ratings based on 100 m road sections in the site are presented in Figure 8-13.

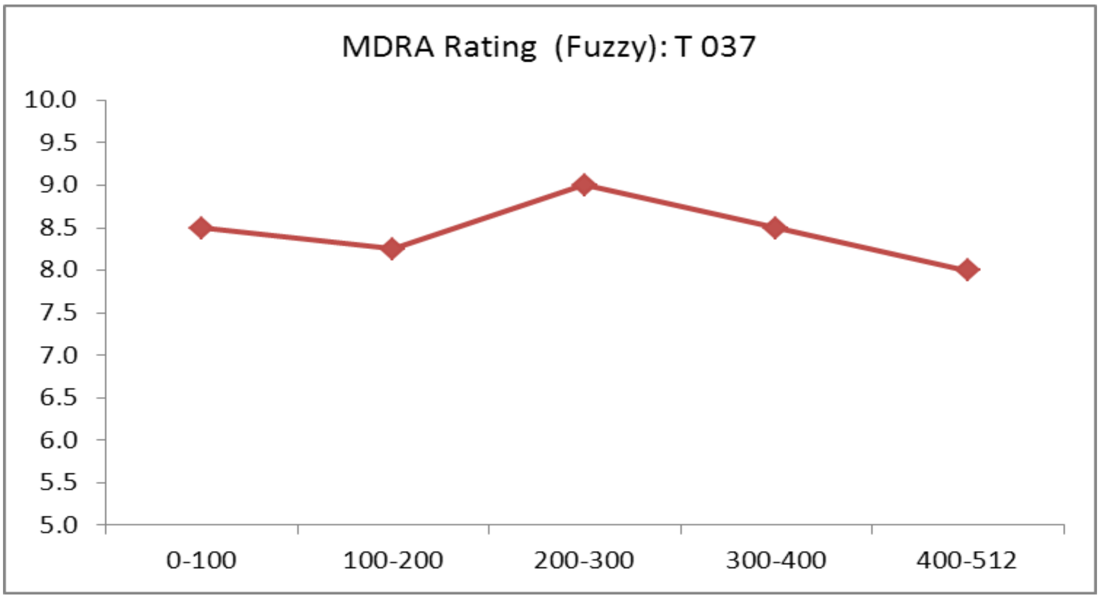


Figure 8-13 MDRA Risk Ratings of 100 m Road Sections in the Site (T 037)

The risk rating of the five, 100 m road sections is very high and the combined rating of the section is 8.5 (combined distribution method). The site has been predicted to be at very high risk based on the MDRA. As the roughness and maintenance cost of the road section is increasing over time and is selected for resurfacing in 2016-17, the site can be considered at very high risk of failure. The drainage of the site is not adequate therefore; the site should be selected for drainage renewal along with the resurfacing in the next year. This proactive drainage can help to increase the life cycle of the road pavements.

2. **Site T 034 (Structurally Unsound Pavement):** The 445 m site was analysed as per the MDRA. The combined risk rating of the site is 8.1 (in the scale of 1 to 10), and successively predicted to be ‘Very High’. Figure 8-14 shows the risk rating of the 100 m road sections in site T 034.

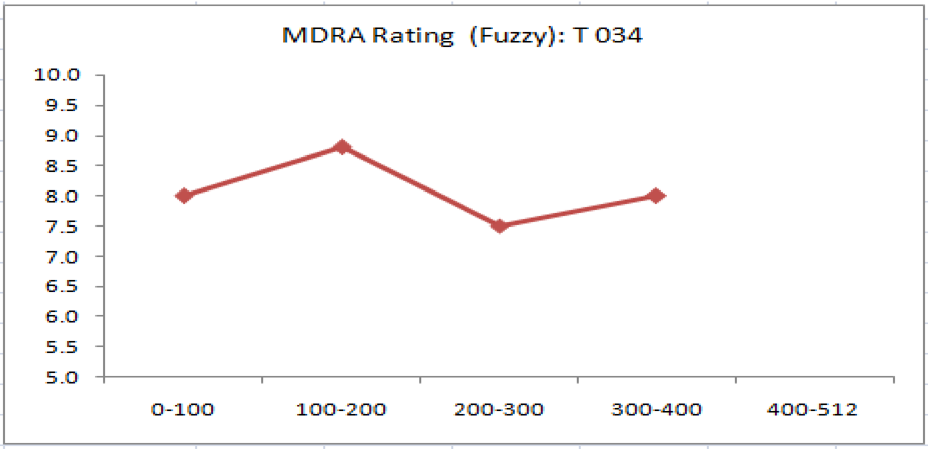


Figure 8-14 MDRA Risk Rating of Site T 034

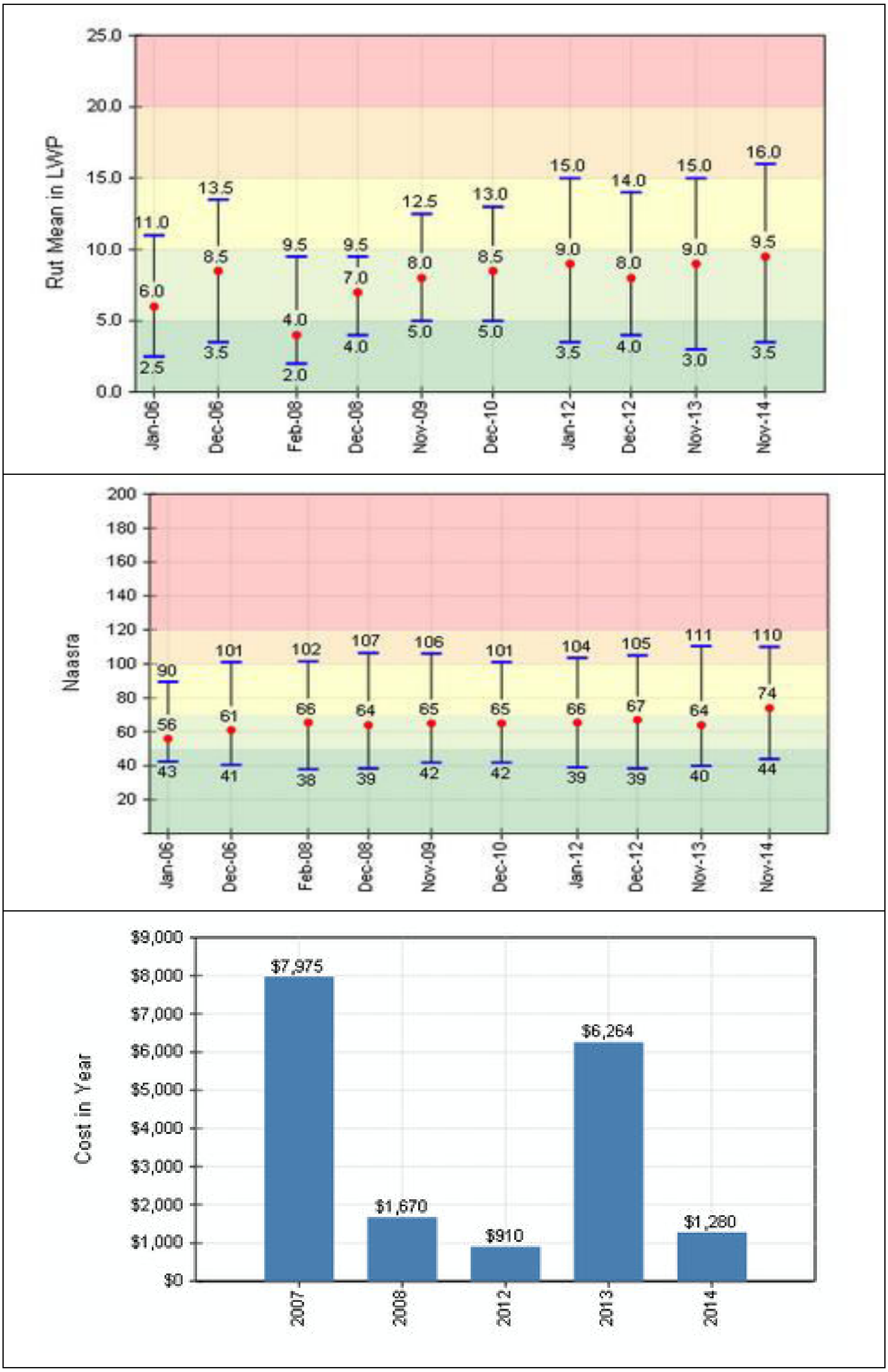


Figure 8-15 Pavement Condition (Rutting and Roughness) and Maintenance Cost Trend (T 034)

The rutting trend in Figure 8-15, indicates that the road section is at risk of failure. The average left wheel path rutting is 9.5 mm and the 90th percentile rutting value is close to the threshold level (in the red zone). The rate of increase in rutting is significant for this site. The increase in average rutting from 4.0 to 8.5 within two years (2008 to 2010) indicates the extent of structural failure due to subsurface moisture. The road pavement possesses asphalt surfacing as explained by the controlled roughness trend as seen in Figure 8-14. The maintenance cost pattern indicates that a moderate intermittent cost is required to maintain the site. The site is programmed for pavement and drainage renewal in 2020/21. Therefore, the site is considered to be at the end of the life cycle based on the FWP and the condition trends. The prediction of the moisture damage risk of the site is in agreement with the actual pavement condition and the maintenance cost trend.

3. **Site T 033 (Failed Pavement)**: This site is programmed for rehabilitation and second coat (resealing) in 2018/2019.

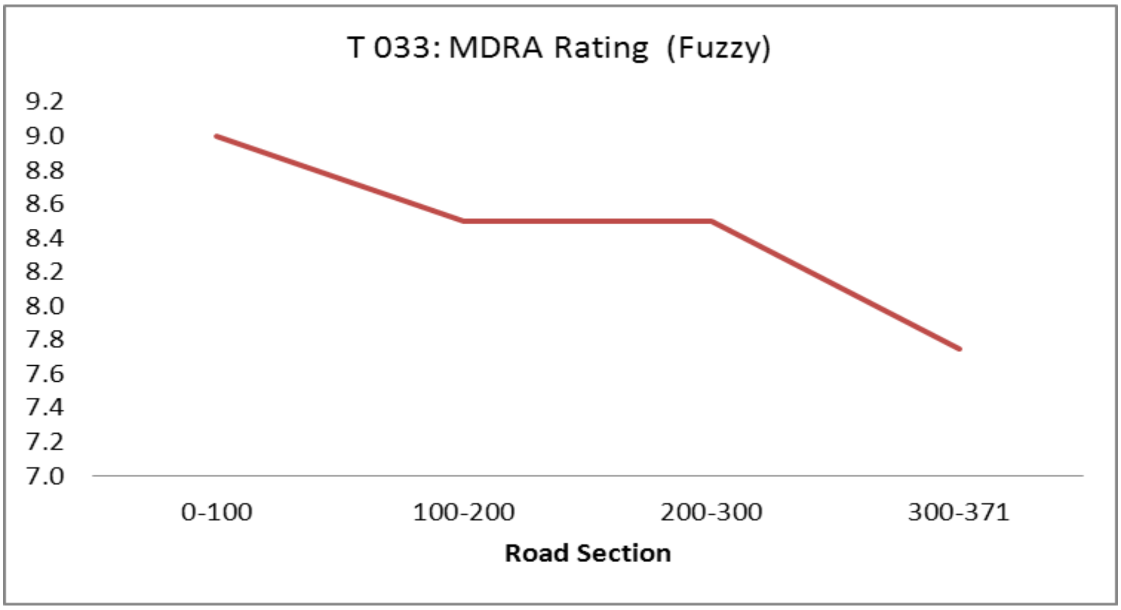


Figure 8-16 MDRA Risk Ratings of 100 m Road Section

The MDRA risk ratings of the road sections (100 m) in Figure 8-16, which show that first three sections are at the very risk of failure due to moisture damage. Overall the combined risk rating of the site is 8.4 (very High) in the scale of 1 to 10.0.

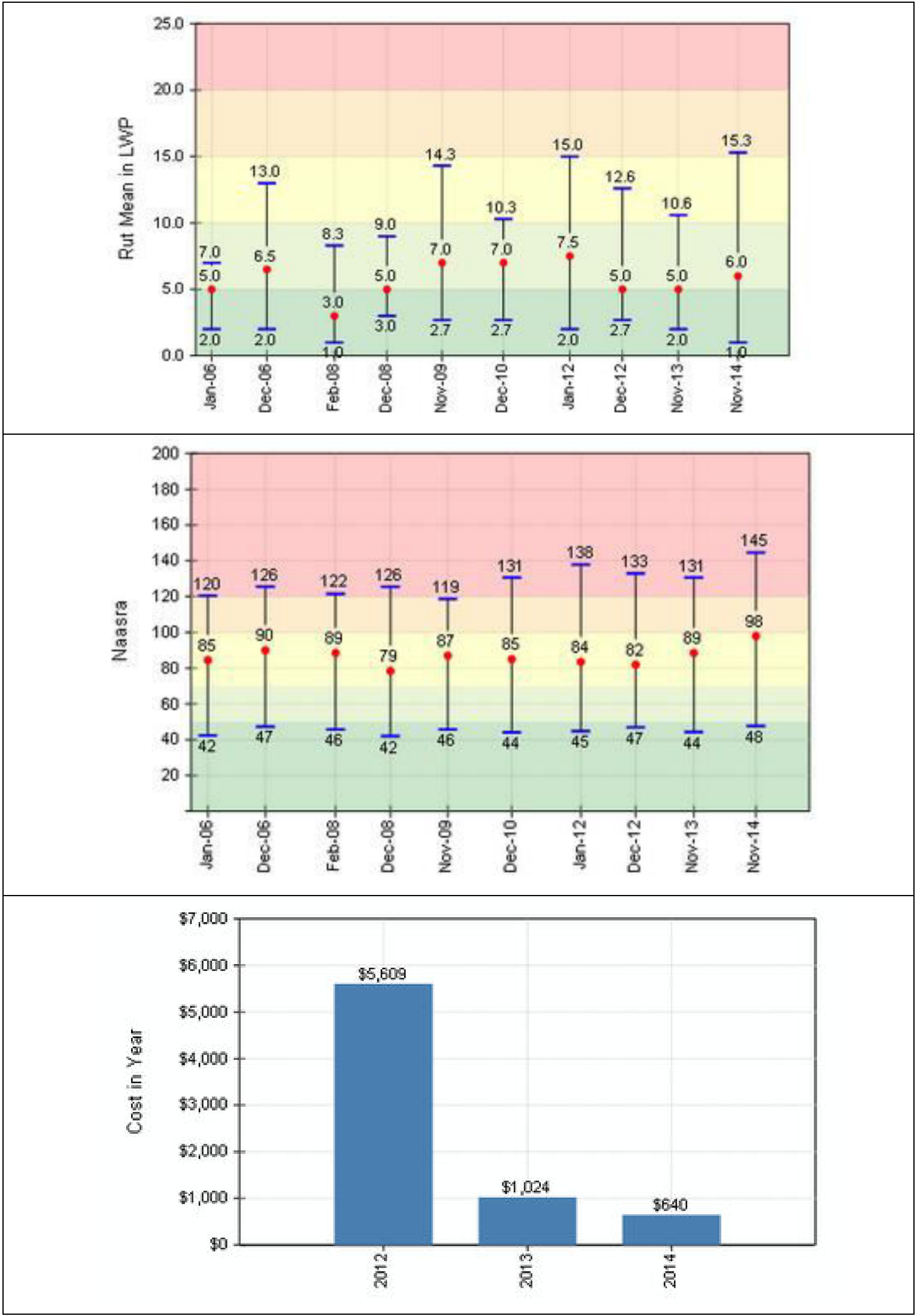


Figure 8-17 Pavement Condition (Rutting and Roughness) and Maintenance Cost Trend (T 033)

Both the rutting and roughness trends (Figure 8-17) indicate that the site is at close to failure due to widespread rutting and the level of service is poor due to excess roughness. The increase in average rutting from 3.0 to 7.0 within a year (2008-2009) indicates that the site is at risk of failure. Although the average left wheel path rutting is low in 2014, the 90th percentile (rutting and roughness) values indicate that the site is at the end of life cycle and the FWP also supported this condition. Subsoil drains will be installed in the first 200 m of the road section. This would reduce its future risk of premature failure due to moisture damage. Overall, the predicted risk by the MDRA and the FWP and the condition tends of the site can be considered to be corroborated.

4. **Sites T 028 and T 029 (Surface Failure)**: These two sites are programmed for resurfacing in 2017/18. During the MDRA analysis, these sites were found to be at very high risk. The risk assessment also warranted for preservation activity to increase the life cycle of the road pavement.

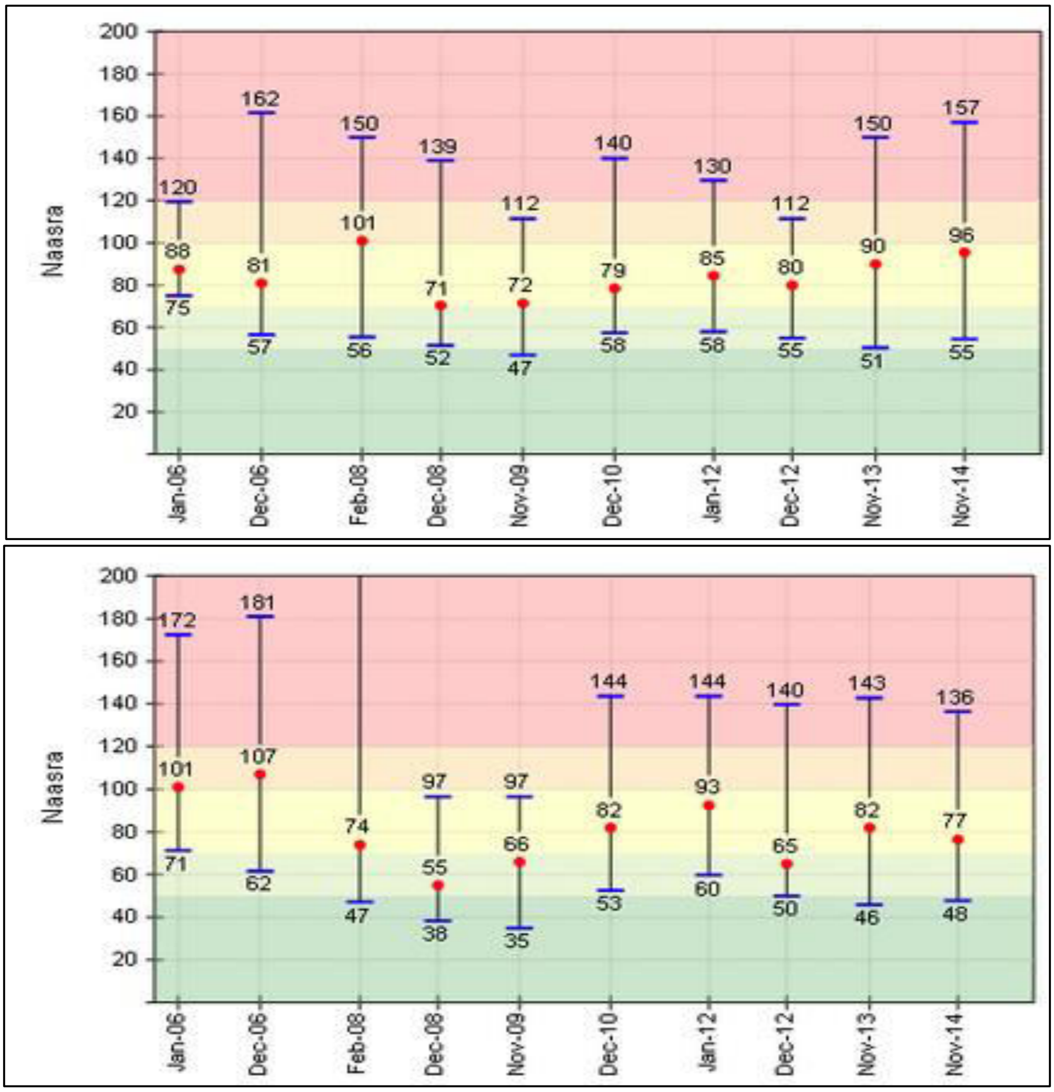


Figure 8-18 Roughness Trend (NAASRA) of the sites T 028 & T 029

The roughness trends of the sites T 029 are presented in Figure 8-18 (top). The rate of increase in roughness from 2008 to 2010 indicates that the site may have potential issues with moisture damages. The site has higher ranking due to the geophysical characteristics, heavy commercial vehicle, high water table and the pavement profile (cut and fill) factors. Similarly the roughness trend of the site T 028 (bottom) also indicates that it has reached its critical point for surface failure. The 90thpercentile roughness (NAASRA) values are increasing at an accelerated rate and crossed the threshold level in November 2013.The MDRA analysis suggested for immediate requirement of any preservation activates to reduce the moisture damage risk. The proposed resurfacing would reduce the risk rating of pavement strength and drainage factors which essentially would reduce the risk of the site.

5. **Sites T 008 and T 009 (High Maintenance Site)**: The MDRA predicted these two sites to be at moderate to high risk of moisture damage. The MDRA risk ratings of both the sites are presented in Figure 8-19.

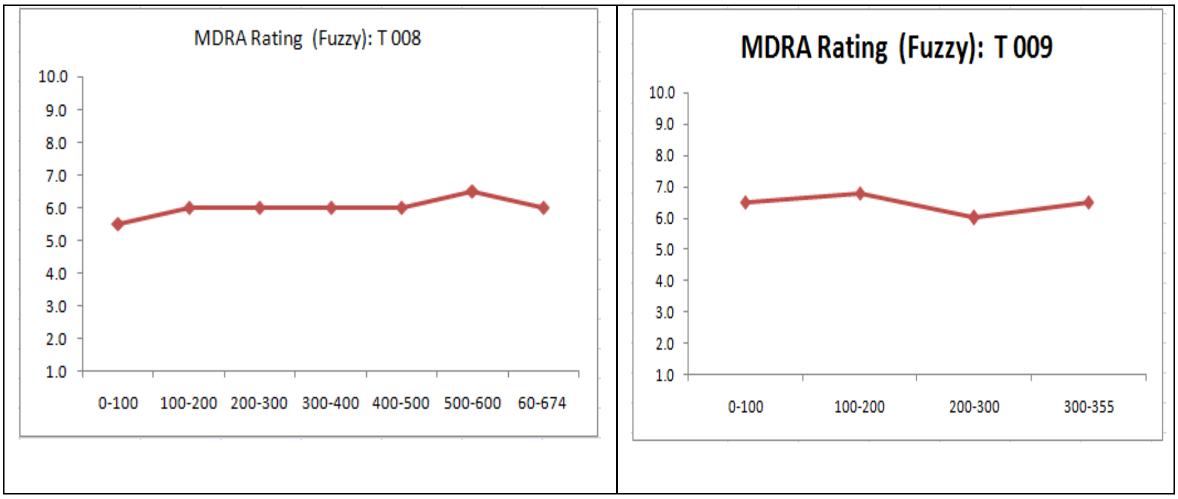


Figure 8-19 MDRA Risk Ratings of Site T 008 and T 009

They are programmed for rehabilitation within the next five to ten years. The pavement condition in site T 008 (Figure 8-20) indicates that the site was at higher risk of failure. However, the maintenance works from 2010 to 2013, helped in resetting the left wheel path rutting and roughness. The rate of increase in rutting and roughness from 2010 to 2012 indicates that the site is at risk of premature failure. During the field investigation, the geophysical and drainage catchment characteristics of the site were found to be contributing the higher risk of moisture damage. The road pavement has been repaired through stabilisation patches. Recent subsurface investigation and FWD tests indicate that the pavement is structurally sound and drainage risk factors are not significant.

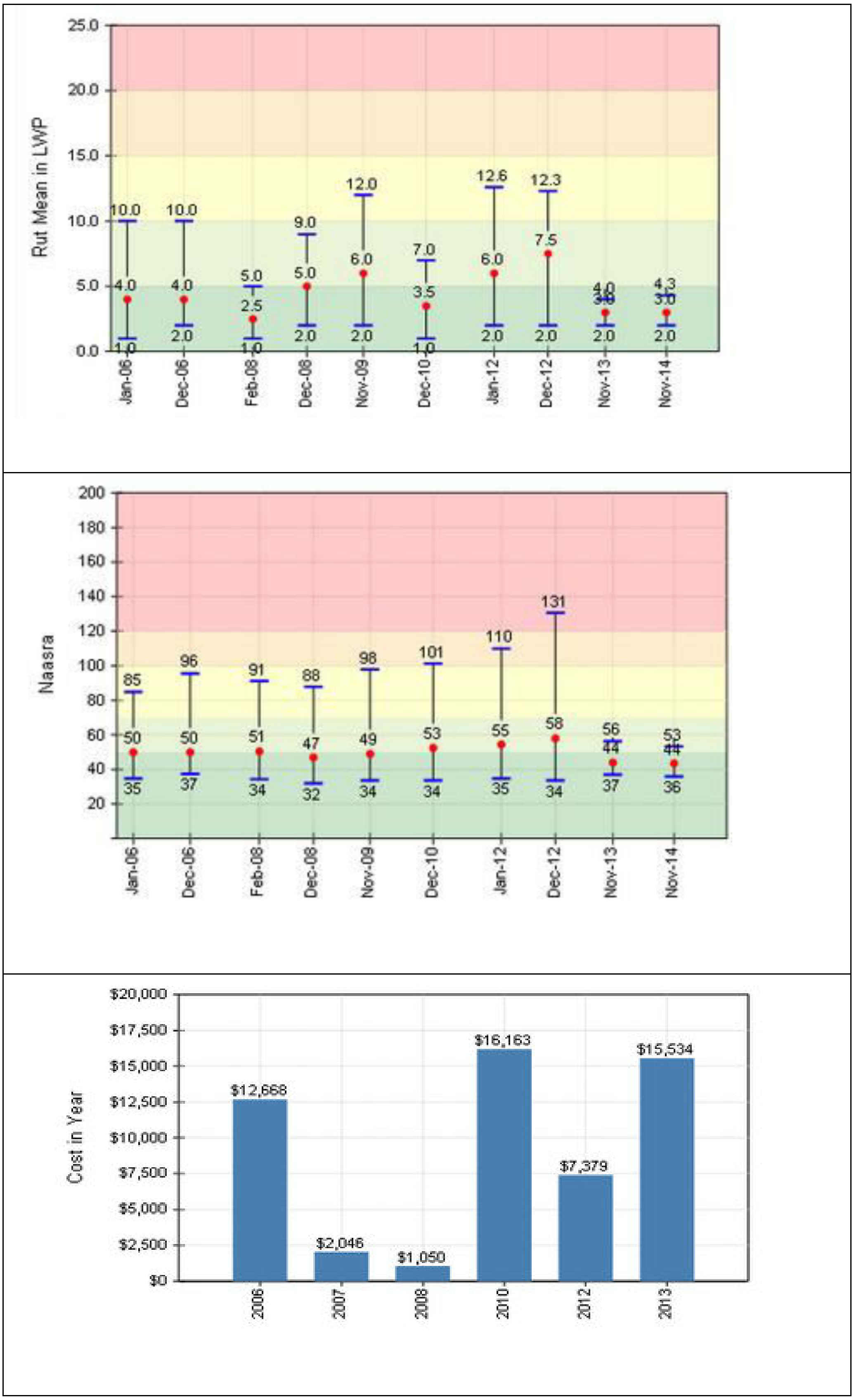
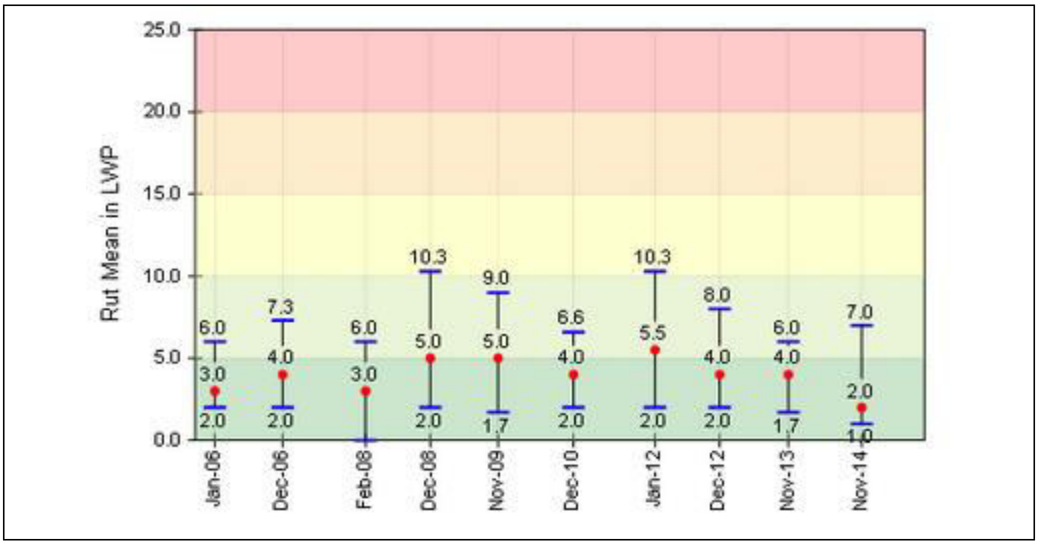


Figure 8-20 Condition and Maintenance Cost Trend (Site T 008)

The pavement condition in site T 008 (Figure 8-20) indicates that the site was at higher risk of failure. However, the maintenance works from 2010 to 2013, helped in resetting the left wheel path rutting and roughness. The rate of increase in rutting and roughness from 2010 to 2012 indicates that the site is at risk of premature failure. During the field investigation, the geophysical and drainage catchment characteristics of the site were found to be contributing the higher risk of moisture damage. The road pavement has been repaired through stabilisation patches. Recent subsurface investigation and FWD tests indicate that the pavement is structurally sound and drainage risk factors are not significant. Overall the prediction of the risk by the MDRA has been well supported by the condition trends and the programmed treatment of the site. Similarly, the site T 009 has been programmed for resealing in 2015. The pavement condition and the maintenance cost trends are plotted in Figure 8-21. Overall the prediction of the risk by the MDRA has been well supported by the condition trends and the programmed treatment of the site. Similarly, the site T 009 has been programmed for resealing in 2015. The pavement condition and the maintenance cost trends are plotted in Figure 8-21.



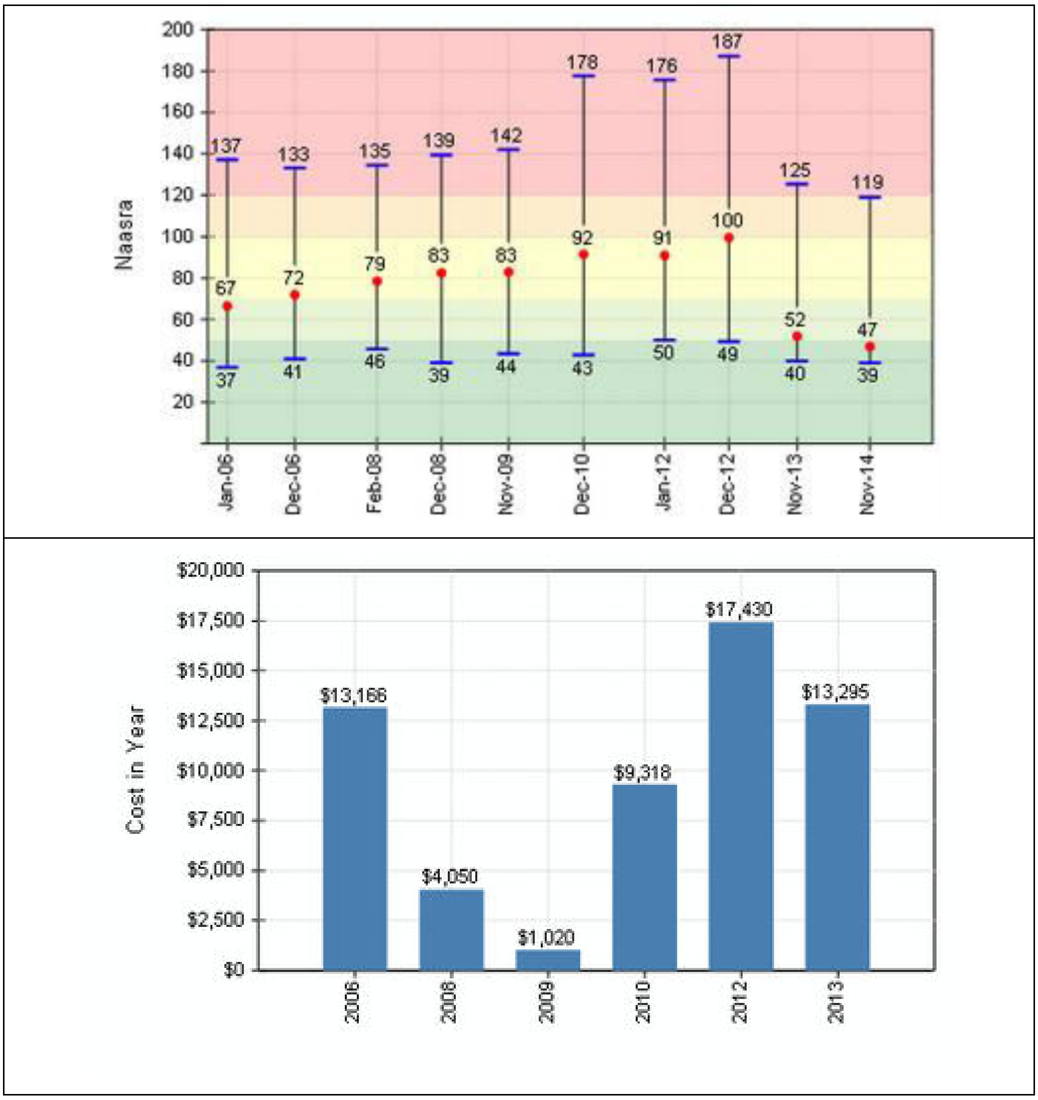


Figure 8-21 Rutting, Roughness and Maintenance Cost Trends of Site T 009

The site was rehabilitated in 2002 so it is still within the first half of the life cycle. The left wheel path rutting of the site indicates that the site has no major structural problem. The roughness of the site increased at a steady rate from 2008 to 2012. The maintenance cost trend shows that roughly around $10,000.00 were spent for annual maintenance of the site. This had helped in resetting both the rutting and roughness values of the site. During recent field inspection in 2015, the rutting and roughness progression were found steady. The post-maintenance FWD test on the site indicated that the pavement layer is integral with little moisture at this stage. However, the site geography, drainage catchment and heavy commercial vehicle count will continue to increase the risk of moisture damage and eventually it may need a major rehabilitation after 10 years.

6. **T 012 and T 013 (Sound Pavements):** These two sites were predicted to be at low to high risk of moisture damage at this stage. The site was rehabilitated in 1998/99. The rutting and roughness trends of the site T 012 are plotted in Figure 8-20.

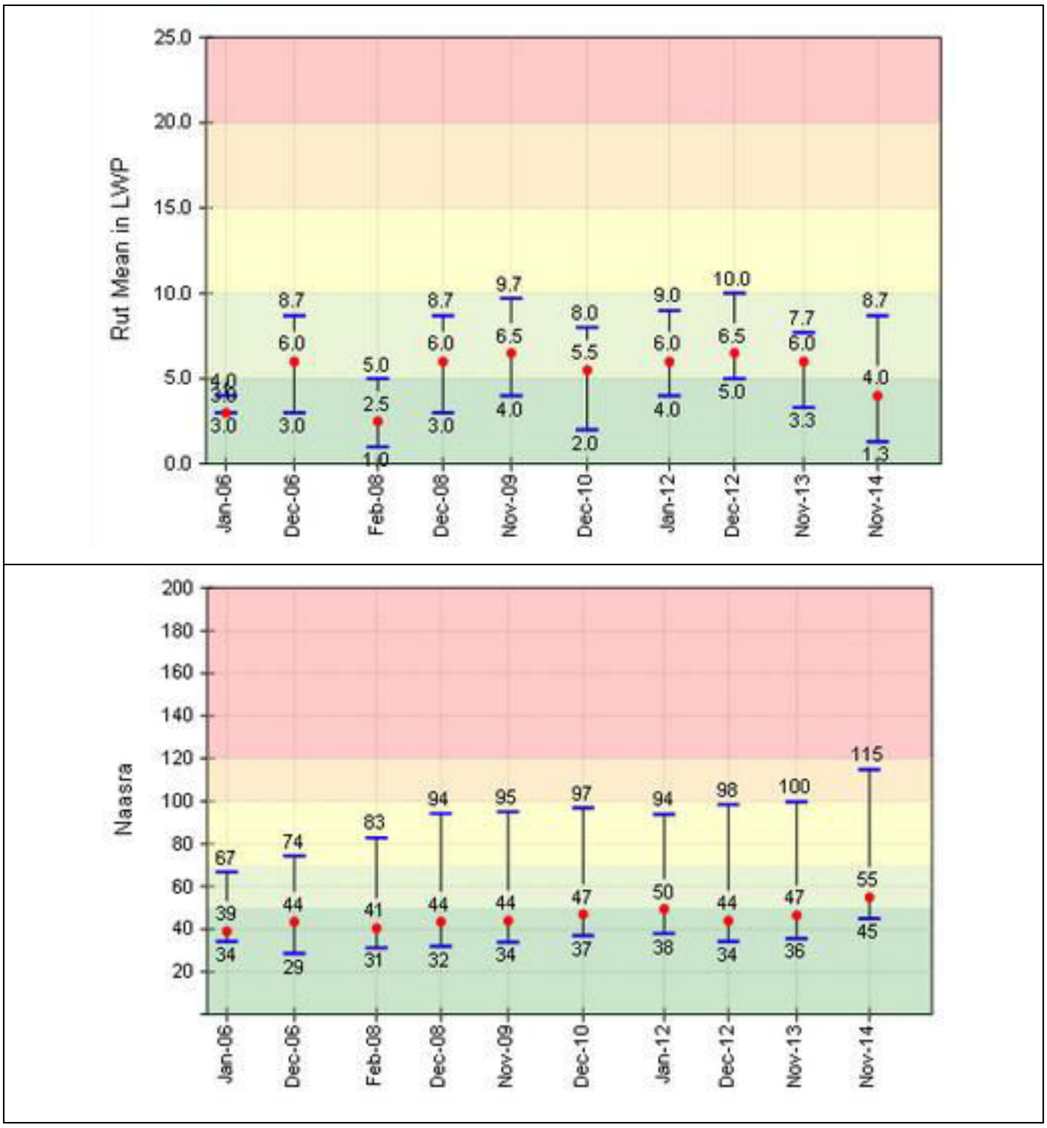


Figure 8-22 Increases in Rutting and Roughness (T 012)

The relatively stable rutting (left wheel path) and the roughness indicates that the site may not be at risk due to structural and surface failure at this stage. This site is programmed for resurfacing in 2024. The roughness of the site is increasing due to the uneven surfaces due to the stabilisation patches in 2013.

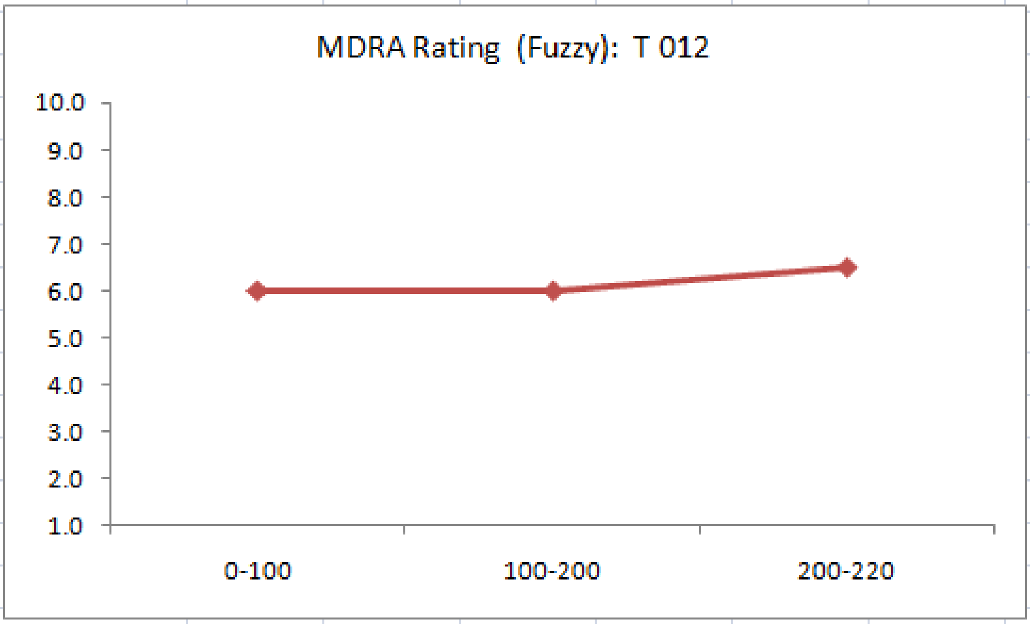


Figure 8-23 MDRA Risk Rating of Site T 012

The MDRA risk analysis report of the site T 012 has been plotted in Figure 8-23. The combined risk rating (6.0) of the site (T 012) seems to be conforming to the actual pavement condition (Figure 8-22) and the programmed treatment in FWP.

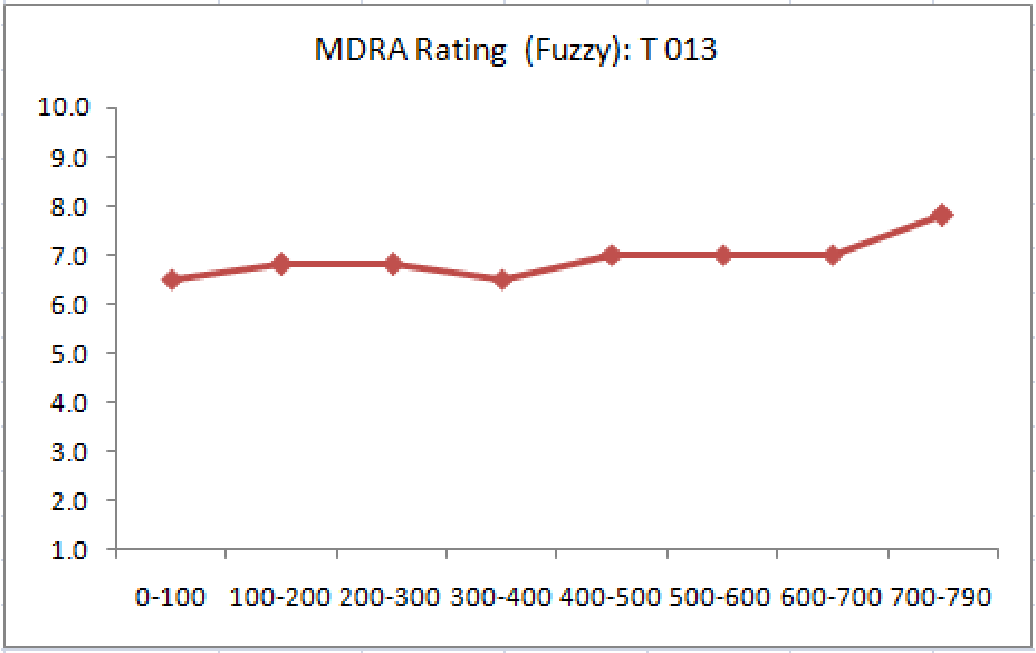


Figure 8-24 Risk Rating (MDRA) of the Site T 013

The MDRA risk ratings of the road sections in site T 013 is presented in Figure 8-24. The site T 013 has a combined risk rating of 6.9 (high) in respect of moisture damage. The site was rehabilitated in 2005 however, the roughness value is increasing at a steady rate (Figure 8-25). The rate of increase in roughness indicates some surfacing issues in road pavement. The site is programmed for a major rehabilitation in 2028/29. The predicted risk rating indicates that the site is not in imminent threat of failure. Rather, resurfacing and drainage improvement within the next five years would reduce the intrusion of moisture into the pavement. The resurfacing would increase the life cycle of the pavement and the moisture damage risk would reduce from high to low. This would help to delay any major rehabilitation and may extend the life cycle of the road pavement.

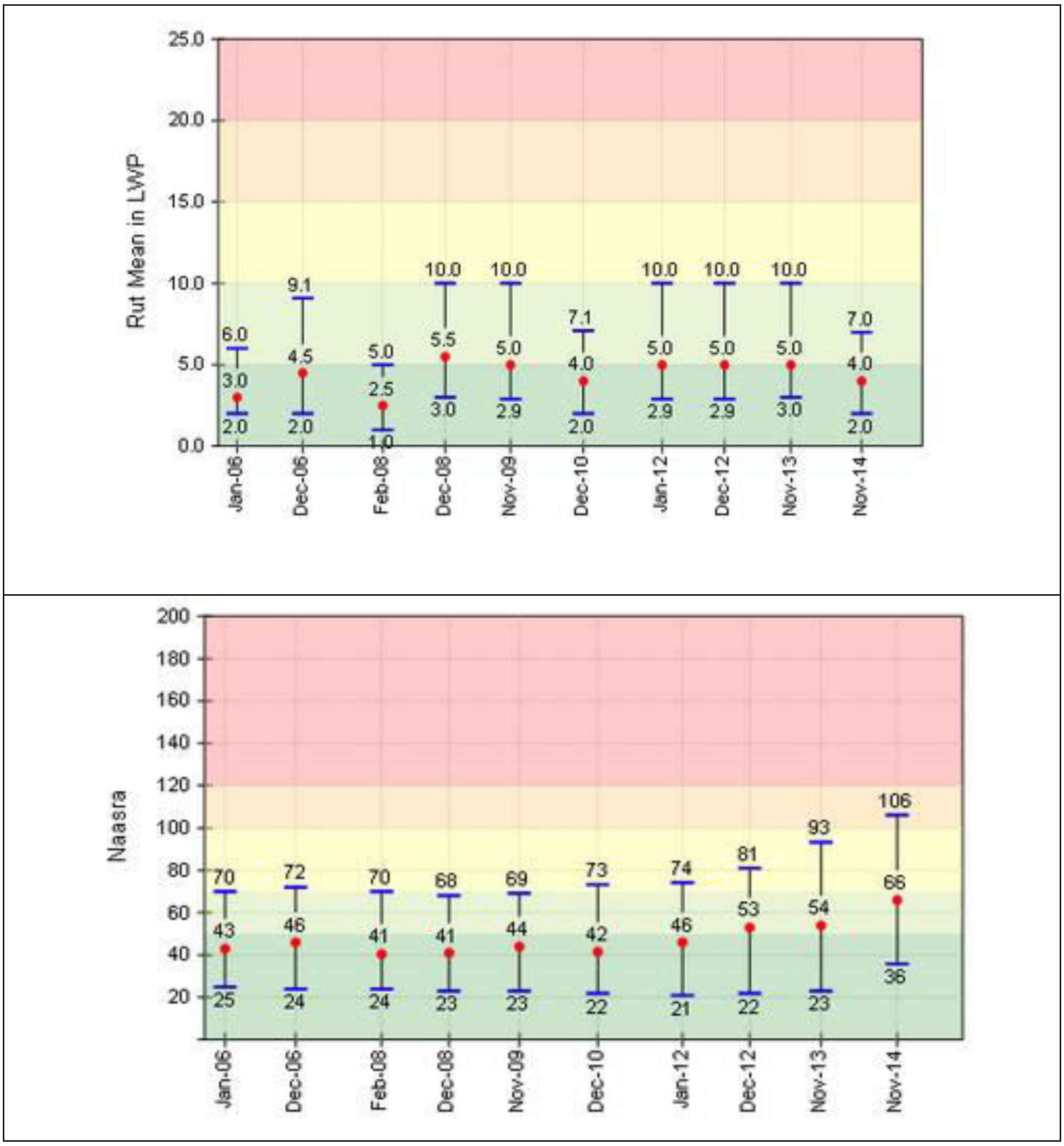


Figure 8-25 Flat rutting, Steady Increase in Roughness (T 013)

8.4.2 Trend Assessment of the Road Section

In addition to the above case studies, the average rutting (left wheel path) and the roughness (NAASRA) distribution of the 15 km road section are plotted against the risk rating distribution in Figure 8-26. The left wheel path rutting data collected in 2013 (red) and 2014 (blue) are plotted in the top two boxes. The longitudinal distribution of the MDRA risk ratings is also plotted in Figure 8-26, to compare with the rutting and the roughness (NAASRA) values of the sites. The average left wheel path rutting and the roughness of the first 7.5 kilometres are found to be below the threshold level. Here in this network, the left wheel path rutting of 10.0 mm and the roughness value of 100 are considered to be as the threshold values. In addition the average rutting (left wheel path) and the roughness value of this sites seemed to be decreasing in 2014 compared to 2013. This may be due to heavy maintenance works in those sites during that time. This 7.5 km road section (T 001 to T 017) is predicted to be at moderate to high risk through MDRA risk analysis. Only four sites in the 7.5 km road sections were predicted to be at very high risk. More than two-thirds of the sites in this section are found to be at very high risk. The left wheel path rutting values from 7.5 to 15.0 km road section is found to reach the threshold level in most of the sites. The comparison of sites (T 020 to T 038) increased level of wheel path rutting with the MDRA prediction indicates the potential implication of moisture damage risk rating in identifying the risk of premature failure. The roughness pattern of the road section (from 7.5 to 15.0 km) also indicates the higher level of risk of the sites as predicted by the MDRA. Therefore, the average rutting (left wheel path) and roughness pattern of the road sections can be compared with the distribution of the predicted risk by the MDRA (Figure 8-26).

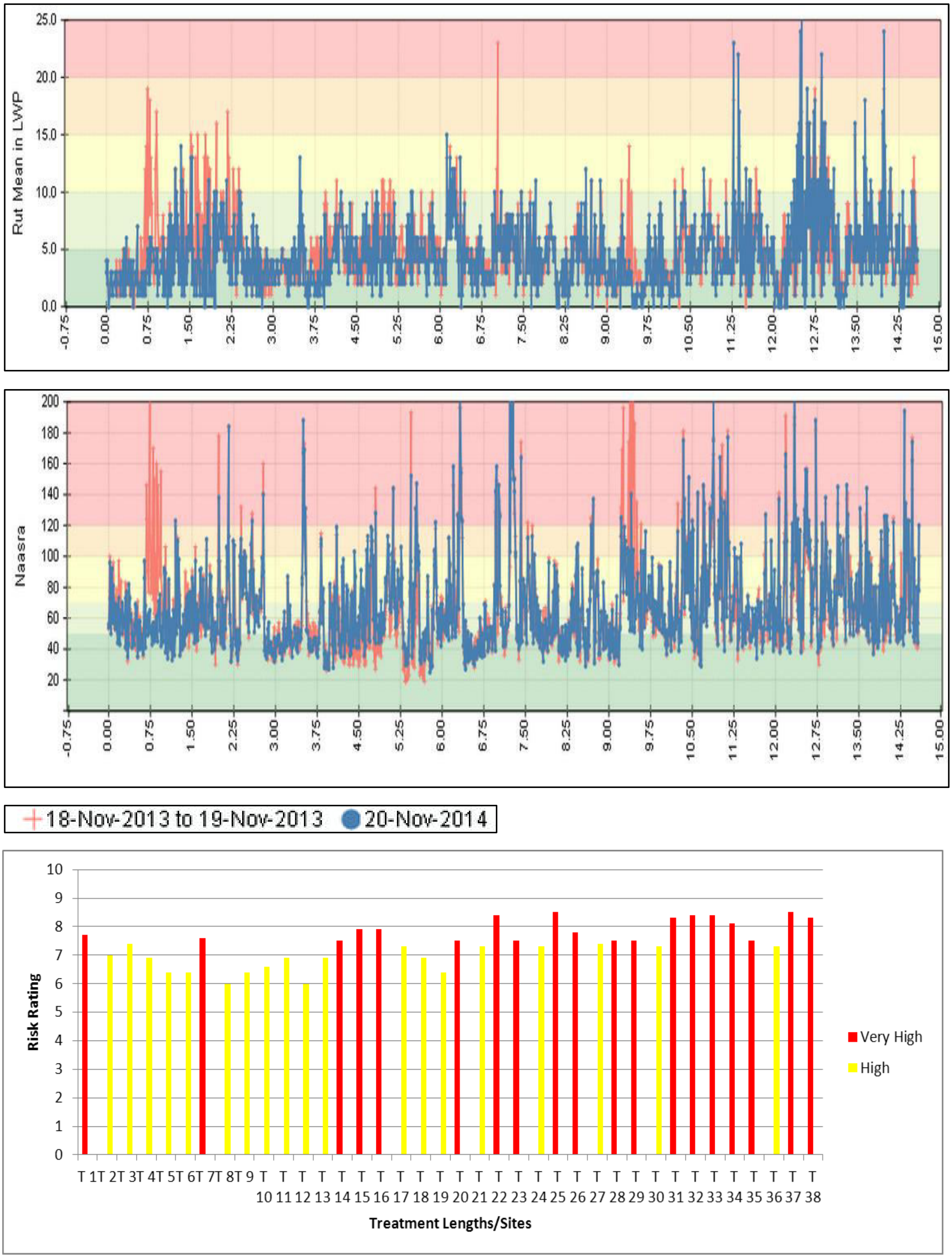


Figure 8-26 Distribution of the Rutting and Roughness and the Moisture Damage Risk Rating of the Road Sections (15 km)

8.5 Discussion

Overall the evaluation of the MDRA in the case studies in Section 8.4 identified the application of the MDRA on the overall maintenance strategy of a road network. First of all, the MDRA can be considered as one of the frameworks used for short and long term planning of pavement preservation activities in a road network. Therefore, the outcome of the case studies and trend analysis in this chapter can be used to develop a maintenance decision strategy based on the MDRA framework and others such as FWP, pavement condition rating and maintenance cost trends. The road sections prioritised through these frameworks (moderate, high and very high) can be compared to the groups (Low, High, Very High) of road sections based on the MDRA. The relative association of these groups of road sections can provide guidelines for developing the optimum maintenance strategy for a road network. Based on this the implications of MDRA in maintenance decision, especially on drainage needs assessment have been presented in the next Chapter. In addition, the outcome of the research has some implications on detecting the need for proactive drainage in the network. The evaluation of the MDRA, especially the knowledge gained through the case studies would help in identifying the areas where the proactive drainage can play a vital role in reducing the risk of failure and expensive maintenance in the network.

8.6 Summary

The case study based evaluation method was used to evaluate the application of the MDRA. The MDRA was updated and presented at the beginning of the chapter. A 15 kilometre road section was analysed through MDRA and the risk ratings of each of the 100 m road sections and the combined risk ratings of the 38 treatment lengths were presented. Then the distribution of the MDRA risk ratings of the treatment lengths was compared to the proposed forward works programme. As the FWP was developed through the deterioration modelling and network condition assessment, the identified correlation between the two frameworks (MDRA and FWP) helps in evaluating the performance of the MDRA. The outcome of the case studies suggested that the MDRA could be utilised to identify the road sections where the drainage improvement can reduce the risk of premature failure and increase the life cycle. The MDRA can be used also as a framework to assess the drainage need and to develop the drainage forward work programme of a road network. These two concepts are further explained while summarising the outcome and application of the research findings in the next chapter.

Chapter 9: Discussion

9.1 Introduction

This thesis documented to development of a framework that can be implemented in any New Zealand road network for identifying the drainage needs. Drainage is an important road network asset that is installed in road sections where the pavement is at risk of failure due to excess water. Excess water in the pavement structure accelerates the deterioration of the road pavement at different stages of the life cycle. The development of pavement distress due to excess moisture was briefly explained in the literature review and, later on, the framework was formulated to assess the risk rating at different stages of the road pavement. This chapter summarises the outcomes of the research, the implications of the research findings and the recommendations based on the knowledge and experience gained during the research. Overall, the research outcomes were encouraging and accepted both in the wider academic community and within the practitioners in road asset management.

9.2 Outcome of the Research

The major outcome of the research is the MDRA framework. The framework was tested for utilisation in drainage needs assessments of road sections. It was used in predicting the moisture damage risk rating and has been correlated with the actual performance of road pavements. The correlation of the MDRA suggested that the framework can be used to predict the road sections that are at high risk of failure. In addition to that, the output of the framework was correlated with the FWP of the road network that was developed based on deterioration modelling. Overall, the MDRA was comprehensively validated based on the actual performance and other predictive frameworks used in road asset management.

The MDRA includes two major steps i.e. ‘risk identification’ and ‘risk analysis’. The ‘risk identification’ includes the evaluation of the moisture damage parameters, which essentially indicates the extent of the moisture damage factors. These moisture damage factors were analysed to develop the risk rating that can be used for prioritising the road sections for drainage improvement. Initially three candidate risk analysis techniques were used in the

MDRA. The risk analysis techniques were used to assess the moisture damage and associated failure risk of road sections. ‘The fuzzy logic model’, the ‘FTA’ and the ‘Combination of Moisture Damage Factors’ are the three candidate techniques used in the research. The techniques were compared based on their performance in risk assessment and several other parameters. Based on the comparative study, the MDRA was further developed to include fuzzy logic and the combination of moisture distribution factors as the suitable risk analysis techniques.

The concept of MDRA is comparatively new as adopted in this research. Moisture damage is a complex issue in road network maintenance. It refers to both the surface and sub-surface distress mechanisms in road pavements that have been caused by ingress of excess water in the pavement. Although the term MDRA has been selected for the study, the aim was to develop a risk assessment framework that can eventually predict the deficiency of drainage in the road network. The selection of the term ‘moisture damage risk assessment ’was always arguable and an alternative could be ‘drainage risk assessment’ of the road sections. The drainage risk often denotes the perceived risk of drainage structures of the road network. Ideally, the priority of the research was to develop a framework that can potentially evaluate and provide a comparative rating based prioritisation for the road sections. This is linked to drainage improvement programmes and the framework has been considered to fulfill the requirement of a practical tool forprioritising the road sections for the programme.

NZTA funded research in 2014 that suggested the need for the development of a scoring based prioritisation framework drainage needs assessment. The proposed scoring based chart included a number of synonymous factors used for this research. They have proposed to include a comprehensive risk assessment technique in the drainage needs assessment of road section (Patrick et al., 2014). The framework developed in this research fits well in this perspective. It includes a comprehensive framework based and developed on knowledge from literature reviews and fieldwork. A number of applied risk analysis techniques were primarily tested as part of the framework. Finally, the framework included the risk analysis technique based on the comparative analysis (Chapter 7) and to meet the requirement of network drainage needs assessment. Overall, the framework has advanced the knowledge and practices in both the academic and commercial areas of drainage needs assessment.

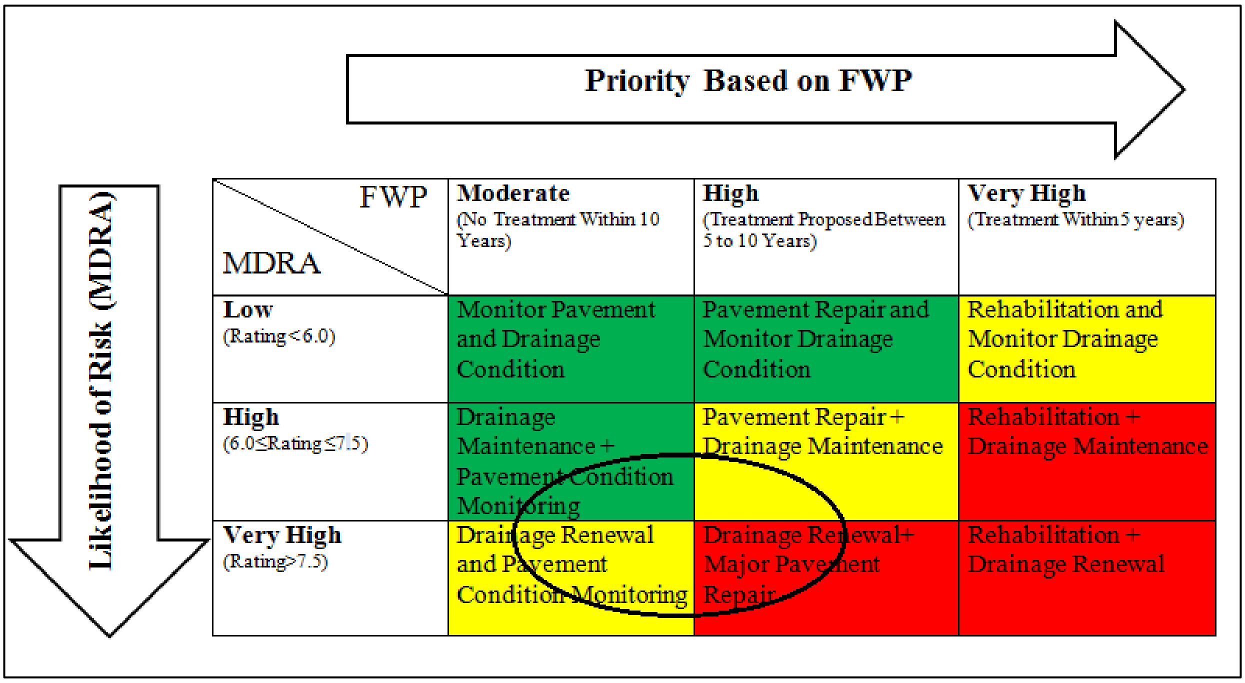
The application of the fuzzy logic model in road asset management is one of the major components of the research. One important aspect of the research was to develop a risk assessment framework based on subjective judgement of experts. People’s perception about risk are expressed through linguistic expressions such as ‘High’, ‘Low’, ‘Likely’, or ‘Unlikely’.

This fuzzy logic model has the capacity to accommodate these linguistic expressions in risk assessment and produce rating-based prioritisation criteria. Although the output of the risk analysis (fuzzy logic) is dependent on the predefined inference rules, the evaluation of the moisture damage factors (Inputs) based on a number of road pavement parameters has increased the reliability of the analysis technique. The fuzzy logic model has been successfully adopted in a number of multidisciplinary researches; however, this attempt to use it for risk analysis in road asset maintenance and management is a unique contribution of this research.

The combination of moisture damage factors technique was effective in determining the combined risk rating of the treatment length or site. The moisture damage parameters adopted for this study change frequently along the road sections in the network. For example, the geophysical features may vary from flat ground to side hills or a large stream among the road sections of a treatment length/site. Therefore, this study has considered 100 m road section as the unit for risk analysis, especially for the fuzzy logic model. The treatment length or site is usually a road section between 0.5 and 1.0 km long. This makes the evaluation of the moisture damage factors of a treatment length or site difficult because the parameters vary significantly among the road sections. Therefore, it is not feasible to use a single rating for each of the moisture damage factors of a treatment length/site. Similarly, it is also not feasible to use the combination of expert judgment in assessing 100 m road section. In that case, the road section has to be sub-divided into smaller (20 m) subsections. It is also highly unlikely that the moisture damage parameters of these sub-sections will vary and produce different distributions for risk analysis. Based on this, the strategy to utilise 100 m road sections for risk assessment seems to be reasonable. NZTA has adopted a similar strategy; their prioritisation process is based on an assessment of 100 m road sections. Once the 100 m road sections are evaluated for the parameters, the moisture damage factors of the treatment length are used to form the distribution curve. All of the distribution curves are superimposed based on their weights to develop a combined distribution curve. This curve is utilised to develop a risk rating for the treatment length. This is particularly important because the risk ratings of the treatment length can be used for network-level prioritisation of the pavement and drainage renewal works.

9.3 Application of the Research Findings

The MDRA risk rating, along with the FWP, can provide guideline for maintenance needs of a road network. The prioritisation of the road sections based on the proposed treatment in the FWP was correlated with the predicted risk ratings by the MDRA (Chapter 8). The output of the case studies conducted indicated that there is a correlation between the MDRA risk rating and the priorities in the FWP. In addition, the MDRA risk rating was found to be in agreement with the maintenance cost trend and the actual condition of the pavement. Therefore, the maintenance strategies or guidelines presented in Figures 9-1 and 9-2 have been developed based on the outcome of the correlation studies. These guidelines can be used for prioritising the pavement and drainage maintenance activities in the road network.



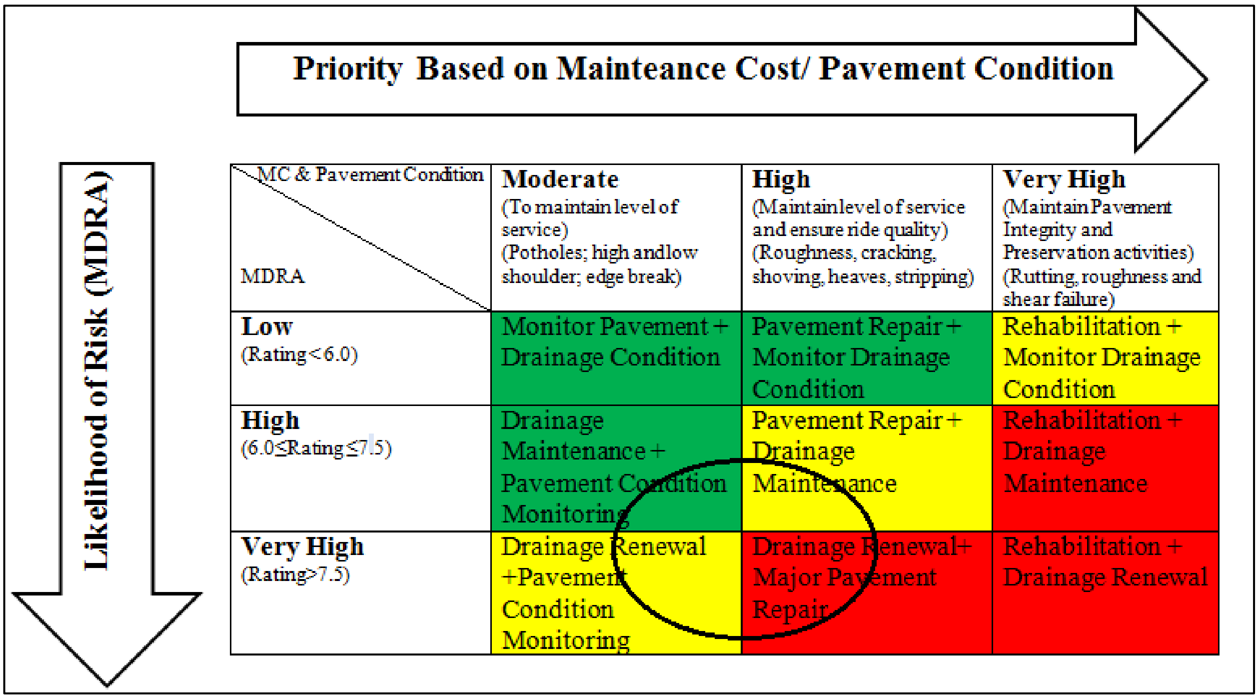
FWP MDRA	**Moderate** (No Treatment Within 10 Years)	**High** (Treatment Proposed Between 5 to 10 Years)	**Very High** (Treatment Within 5 years)
Low (Rating<6.0)	Monitor Pavement and Drainage Condition	Pavement Repair and Monitor Drainage Condition	Rehabilitation and Monitor Drainage Condition
High (6.0≤Rating≤7.5)	Drainage Maintenance + Pavement Condition Monitoring	Pavement Repair + Drainage Maintenance	Rehabilitation + Drainage Maintenance
Very High (Rating>7.5)	Drainage Renewal and Pavement Condition Monitoring	Drainage Renewal+ Major Pavement Repair	Rehabilitation + Drainage Renewal

Figure 9-1 Pavement and Drainage Maintenance Strategy based on MDRA and FWP

The prioritisation of the maintenance work proposed in the FWP can be classified into three groups. The sites selected for a major treatment within the next five years can be considered to be at higher (very High) priority, whereas, those selected for treatment between 5 to 10 years can be considered as ‘High’. The sites that are not in the FWP for any treatment can be considered well enough or recently treated so have been considered in the ‘Moderate’ category. Similarly the final MDRA (Chapter 8) was formulated to predict the road sections into three categories such as ‘Low’, ‘High’ and ‘Very High’. Therefore, any road section or site found to be at low risk of moisture damage and that has not been selected for any major treatment within the next ten years, can be put on hold and regular monitoring of the pavement and drainage condition undertaken. Some of the sites predicted to be at high risk during the MDRA, may not be selected for any major treatment in the FWP. These sites may be at high risk because of the increased ratings of the static factors. Any road pavement rehabilitated within the last five years with low structural integrity may fall into this group because of their complex geography, high water table, high traffic and HCV or that may be located in high stress horizontal curves. These sites have to be prioritised for drainage maintenance such as reforming lined or unlined water channels, and High (shoulder) lip removal. Similarly, some sites may be selected for major treatment within 5 to 10 years; however, they may not be at risk of moisture damage. Usually the roads on flat and rolling ground with low to moderate traffic belong to this category. These pavements are maintained through stabilisation patch repairs to ensure the performance of the network. The drainage conditions of these sites are monitored in order to avoid any unexpected failure. These three groups are presented by the green groups in the guideline (Figure 9-1).

The next group of road sections are those prioritised for major treatment within the next five years, although the drainage risk is comparatively low. Most urban roads with good drainage conditions may fall in this category when they are close to resurfacing or renewal. These roads are primarily selected for pavement renewal and to monitor the drainage conditions. On the other hand, some low volume rural roads may be at high risk of moisture damage, though they may not be prioritised for rehabilitation due to their limited importance in terms of road classification. Road controlling authorities often have to ignore this group of road sections. Therefore, these roads can be selected for installation of subsoil drains, kerb and channel and reforming unlined water channels. These low cost drainage improvements can be effective in increasing the life cycle of the road pavement and ensuring value for money for the drainage investment. The next group of roads in this category are selected for treatment within the five to ten years and the MDRA predicted them as at high risk. Some moderately trafficked roads in the National Strategic and Regional Connector routes belong to this group, and are usually in the last decade of their life cycle. These roads require pavement repair through stabilisation and comprehensive drainage maintenance. These roads should be selected for drainage renewal during the rehabilitation in order to reduce their risk of premature failure. As these roads are of national importance the expenditure in drainage would ensure the value for money for the investment.

The last three groups are presented in the red category of the guideline (Figure 9-1). The road sections selected for a major treatment within five years and predicted to be at very high risk of moisture damage, should receive the highest priority for pavement and drainage renewal. The National Strategic and Regional Connector roads in complex geography with side hills, streams or high water tables belong to this group. When these roads are prioritised for pavement renewal within the next five years, they should be prioritised for drainage renewal as well. Some of these roads may be prioritised for pavement renewal, although their moisture damage risk is not very high. These roads should be selected for pavement renewal and drainage maintenance. On the other hand, some roads may be at very high risk of moisture damage, though they were elected for a treatment between 5 to 10 years. These roads should be prioritised for drainage renewal (if required) or drainage maintenance and major pavement repair. The drainage renewal is expected to reduce the risk of failure and eventually the pavement repair can increase their life cycle. Similar to the above maintenance strategy (Figure 9-1), another guideline was developed outlining the relationship between the risk assessment (MDRA) and the pavement condition and maintenance cost trend of any road network (Figure 9-2).



MC & Pavement Condition MDRA	**Moderate** (To maintain level of service) (Potholes; high andlow shoulder; edge break)	**High** (Maintainlevel of service and ensure ride quality) (Roughness, cracking, shoving, heaves, stripping)	**Very High** (Maintain Pavement Integrity and Preservation activities) (Rutting, roughness and shear failure)
Low (Rating<6.0)	Monitor Pavement + Drainage Condition	Pavement Repair + Monitor Drainage Condition	Rehabilitation + Monitor Drainage Condition
High (6.0≤Rating≤7.5)	Drainage Maintenance + Pavement Condition Monitoring	Pavement Repair + Drainage Maintenance	Rehabilitation + Drainage Maintenance
Very High (Rating>7.5)	Drainage Renewal +Pavement Condition Monitoring	Drainage Renewal+ Major Pavement Repair	Rehabilitation + Drainage Renewal

Note: MDRA (Moisture Damage Risk Assessment); MC (Maintenance Cost)

Figure 9-2 Pavement and Drainage Maintenance Strategy based on MDRA and Maintenance Cost/ Pavement Condition

This guideline (Figure 9-2) would be helpful for road networks that have been maintained based on pavement condition or maintenance cost trends instead of FWP. For road sections that are on the verge of failure due to rutting, roughness, shear failure and excessive maintenance costs, the preferred treatment is to rehabilitate them. If some of these road sections are found to be at very high risk of moisture damage, then they should be programmed for drainage renewal as well. Some of them might be at high risk of moisture damage, and then comprehensive drainage may not be required. However, drainage renewal along with the major pavement repair can be effective in increasing the life cycle of the road pavement if they are at very high risk of moisture damage with moderate pavement distresses such as roughness, cracking, shoving, heaving and stripping. These road sections are heavily trafficked highways in complex geography that are also close to failure due to excessive pavement distresses and are placed in the red categories in Figure 9-1 and 9-2.

Newly rehabilitated roads at low moisture damage risk may not require any expensive repair, so the strategy will be to monitor them for pavement and drainage condition. Usually the newly built urban roads with good drainage fall into this category. Some newly built or rehabilitated rural highways in low risk regions of moisture damage may also be in this category. Some roads start showing excess pavement distresses such as roughness, cracking, shoving, heaving, stripping, mostly after the first chip seal cycle (7-10 years) although they are at low risk of moisture damage. Poor quality material, construction quality and environmental factors such as temperature may have induced failure in the base layer. Often these pavement distresses reduce the ride quality and major repairs through stabilised patches are done to increase the integrity of the road pavement. These roads should be programmed for regular maintenance and monitoring of existing drainage measures. Some rural roads with high traffic and heavy commercial vehicles may have been performing well (low maintenance) and show very little pavement distress. These roads are in the range of 10-20 years of their life cycle and are usually not considered for any major treatment. The MDRA risk rating can prioritise these road sections for drainage renewal and maintenance such as high shoulder lip removal and reforming surface water channels. These should ensure the value for money for drainage investment because the drainage improvement would increase the life cycle of the road pavement and defer any major repair within the contract period. These roads are grouped in the third and fourth rows of the second column in Figure 9-1 and 9-2.

Some roads, especially the National Strategic Highway and urban roads with comprehensive drainage measures, fail due to accelerated rutting, especially at the end of their life cycle. These roads are usually at low risk of moisture damage, however they need to be prioritised for major rehabilitation or renewal due to excessive maintenance cost and pavement distresses such as rutting, shear and cracking. These roads have to be programmed for rehabilitation or renewal along with the maintenance of existing or newly installed drainage measures. Some of these roads can be programmed for drainage improvement (if required) and major repair in order to extend the life cycle of the road pavements. Overall, these two guidelines (Figures 9-1 and 9-2) have demonstrated how the MDRA framework can be utilised along with the other asset management tools inroad network maintenance. This is especially useful when practitioners are keen to identify areas where the drainage can ensure value for money and reduce the amount of expensive maintenance in the road network.

9.4 Overall Understanding on Drainage Needs Assessments

Overall, the research was a timely effort when road network maintenance, especially in New Zealand, is in a dilemma due to the lack of required investment. The dynamic nature of the road maintenance contracts has increased the challenges to ensure the efficient utilisation of limited resources. The industry is keen to move towards lower cost treatment option such as drainage to help in prolonging the life of the pavement. Another strategy is to reduce the amount of expensive preservation and maintenance activities in low volume Regional Connector and Distributor highways. The target is to maintain the road and invest more in drainage or improving resilience to reduce the maintenance cost of the network. In this circumstance the drainage risk assessment based on MDRA can play a crucial role in prioritising the drainage improvement works in the network.

The groups of road sections circled in Figure 9-1 and 9-2 should be of greater interest among the practitioners. Especially the two groups from yellow and one group of roads from the red zone within the circle should be prioritised for drainage improvement. These roads in the red group (3rd row and 3rd column) are mostly the National and Regional Strategic rural highways with high levels of traffic and heavy commercial vehicles. These roads are usually within complex geographic regions with inadequate drainage and have been considered for any major repair within the next five to ten years due to excessive maintenance and widespread pavement distress.

The asset manager should identify these roads and target them for major drainage renewal or improvement. Detailed forensic investigation using the FTA technique can be implemented to identify the source of excess moisture and root causes of the problem. These road pavements should be repaired along with the drainage renewal or improvement. Once the drainage issues are rectified in those roads they will be shifted upward to the green zone and the extent of failure (hopefully) will be reduced. The next priority should be given to the roads (3rd row, 2nd column) that are at very high risk of moisture damage even though they were recently renewed or rehabilitated. The pavement condition and the maintenance cost may not be high, however, due to the abundance of moisture damage factors these roads will shift towards the red zone (3rd row 3rd column). Often these roads are ignored or overlooked in the traditional deterioration modelling or condition rating. Because this traditional modelling method considers the age of the pavement, rate of increase in pavement distresses such as rutting, roughness and cracking. These roads apparently looked fair and they may not require excess maintenance. However, these roads start falling apart without sufficient warning. Besides, this premature failure is considered as a huge drawback for the performance of the road maintenance contractor. The predictive characteristics of the MDRA framework have made it successful in identifying those road sections that are at risk of moisture damage, although they may not be prioritised based on the traditional FWP and condition rating. These roads should be programmed for drainage renewal such as installation of kerb and channel or subsoil drains based on the geophysical background of the site. If the drainage was ignored during rehabilitation of the sites, they should be programmed for regular drainage improvement such as reforming lined or unlined water channels, High shoulder lip removal and removal of high and low shoulders. This would reduce the amount of excess water into these pavements and delay their progression into the red region in Figure 9-1 and 9-2. Therefore, the MDRA can be effective in identifying and prioritising the drainage need and to ensure the effective utilisation of the drainage investment and reducing the amount of expensive preservation activities in the road network.

Another advantage of the MDRA is that it can help in differentiating between the groups (2nd and 3rd row of column 3) of road that are both in the red region (danger of failure) in the above two figures. These roads are at a terminal stage based on the FWP and the pavement conditions and maintenance cost trends indicated that a major rehabilitation is required to preserve the integrity of the road pavements. However, all of these sites may not require improved drainage and often the asset managers face difficulty in demonstrating the applicable tools in prioritising the sites for drainage improvement. The MDRA has the ability to fill the gap and has been demonstrated as a practical tool that can identify the moisture damage risk ratings of these road sections. Detailed forensic investigation should help in selecting the appropriate drainage measures such as installation of kerb and channel, side-drains or subsoil drains for a road section.

Chapter 10: Conclusion

10.1 Research Conclusions

The research aimed to develop a risk assessment framework to identify road sections that are at risk of premature failure due to excessive moisture. These road sections can be prioritised for drainage improvement. Therefore, the overall aim of the research was to develop a framework or methodology that can be used to assess the drainage need of a road network. Drainage needs assessment is crucial in road network maintenance. It is mostly targeted to reduce the risk of failure and, thus, to increase the life cycle of road pavements. The background study and literature review indicated that there is scope for developing the framework that can be utilised for drainage needs assessment. This is particularly important for a performance based road network where the road controlling authority has to be proactive in prioritising the drainage improvement programmes. There has been a major drive in New Zealand to invest more in drainage improvement as it is expected to increase the life cycle of the pavement.

The research was conducted in one of the performance based State Highway road networks in New Zealand. The road controlling authorities were keen for a framework that can be used for prioritisation of the drainage improvement works within the limited resource. A preliminary study was conducted, along with the literature review that essentially helped in the conceptual development of the framework. Case studies were conducted in the network to develop and evaluate the risk assessment framework. The moisture damage risk rating of the road section was compared to the actual pavement condition and vulnerability based on the FWP. The outcome of the research has been disseminated among the practitioners through publication in peer reviewed journals, conferences and technical seminars. In addition, the risk assessment framework was used in developing the drainage FWP of the road network. Thus, every effort was undertaken to increase the validity of the risk assessment framework. Overall, the research objectives were fulfilled through the case studies in different chapters of the thesis.

Objective 1: To develop a framework for identifying the road sections those are at risk of premature failure due to moisture;

This objective aimed to develop and demonstrate a practical framework that can fulfil the requirements of a drainage need assessment tool for the road network. The framework presented in Chapter 8 (Figure 8-1) has been developed through a step by step iterative process presented in previous Chapters. Initially, a risk assessment framework was conceptualised based on the literature review and field work. These have helped in identifying the moisture damage factors that are being used as the inputs for the risk assessment. Each moisture damage factor includes a number of moisture damage parameters. These moisture damage parameters determine the extent (rating) of the moisture damage factors. The ratings of the moisture damage factors determine the 'Moisture Damage Risk Rating' i.e. the output of the risk assessment. The risk assessment includes a comprehensive analysis technique based on the length of the road section. Overall, the MDRA has been demonstrated as a predictive framework that can assess the moisture damage risk rating of any road section. The framework has been developed to be applicable to road networks in New Zealand. It can be used for evaluating the moisture damage potential of newly rehabilitated road sections of road pavements that are at the end of their life cycle.

Objective 2: To evaluate the risk analysis techniques in order to select the optimum one for the framework;

The risk assessment framework included three candidate risk analysis techniques. One major objective of the research was to compare the risk analysis techniques based on their performance and other essential features such as speed, reliability, availability, transferability and applicability in drainage needs assessment. The risk analysis techniques were selected based on the literature review and the characteristics of the moisture damage factors and subjective nature of the risk assessment. Initially, the fuzzy logic model, fault tree analysis and combination of moisture damage factors techniques, were employed as part of the MDRA. Case studies in Chapter 4, 5 and 6 showed that the risk analysis techniques are applicable to moisture damage risk assessment of the road sections. However, each of them has proven to be applicable for risk assessment of the road sections in different circumstances. The comparative analysis presented in Chapter 7, includes a ranking of the risk analysis techniques based on performance and a number of other factors. Although the output of the comparative analysis indicated a hierarchy among the risk analysis techniques, all of them were amalgamated into the MDRA framework based on their relevancy at different stages of the risk analysis.

Objective 3: Finally, to verify the reliability and applicability of the framework in predicting the risk of failure of any road network.

Once the framework was developed and modified based on the evaluation of the risk analysis techniques (case studies) and feedback from the practitioners, the evaluation of the reliability and applicability of the MDRA was the final objective of the research. The application of the MDRA framework was evaluated in respect of three frameworks used in road network maintenance. The FWP is the long term maintenance programme of the road network based on deterioration modelling. The drainage risk rating of the road sections was evaluated based on the prioritisation in the FWP. Case studies in Chapter 8, demonstrated that the moisture damage risk rating can identify the road sections that are at high risk based on the FWP. In addition to that, the condition assessment (pavement distresses) is crucial for prioritising the road sections for renewal or rehabilitation. The prioritisation of the road sections in reference to the risk assessment (MDRA) was correlated with the actual condition (pavement) of the road section. The road sections at very high risk of moisture damage were found at terminal stages due to pavement distresses and maintenance cost. Usually the maintenance cost of a road section becomes uneconomical at the end of the life cycle and warrants for a major rehabilitation or renewal of the road pavement. The risk assessment by the MDRA was also evaluated based on the historical maintenance cost trend of the road sections. Overall, the assessment of the road sections based on the MDRA was comprehensively corroborated with the prioritisation based on the FWP, pavement condition assessment and maintenance cost trend.

10.2 Limitations of the Research

The MDRA was developed and evaluated based on the data from a State Highway road network in New Zealand. A brief description of the road network was presented in the methodology section (Chapter 3) of the thesis. This road network was selected in order to fulfil the requirement of the research project. It is one of the major State Highway networks and can represent the major rural highways in New Zealand. However, the MDRA can be applied in any road network with required modification and calibration in the moisture damage factors and their root causes or parameters.

The risk analysis techniques used in the study, especially, the fuzzy logic, FTA and the combination of moisture damage factors (model risk) are commercially available programmes. These programmes were available through the academic licenses and applicable to research and education purposes only. The calculation methods in risk assessment of these techniques are not transparent or open to the user, especially, the fuzzy logic model which is often termed as a ‘black box’ model. The estimation of the risk rating (output) based on the ‘If-Then’ based inference rules and the membership functions (inputs) are not open to the user. Therefore, it is difficult to replicate the risk analysis technique using other programming languages.

The risk assessment through MDRA involves subjective expert judgement. Expert judgement is required to assess the moisture damage factors (inputs) however, the moisture damage parameter table (trigger based) essentially guides the risk assessment. The framework requires evaluation of the sites either through the video survey or physical inspection. This may be a drawback of the model. Although most of the moisture damage parameters can be obtained from the road asset management databases or field tests, it will require inspecting the road sections to identify the geophysical factors.

The MDRA involves the evaluation of the pavement strength based on the FWD deflection measurements. The scopes of the FWD tests and its various parameters for evaluating the effect of moisture on road pavement were enunciated in the literature review chapter. Based on this, the FWD tests were utilised in evaluating the strength of the road pavement. The lack of the available recent FWD test data for the road network was a constraint in the research. The last network level FWD tests were conducted in 2007. More recent, network wide, FWD test data would be helpful in evaluating the longitudinal profile of the road pavement (strength). However, the FWD tests on the network are frequently conducted mostly in the road sections that are being selected for rehabilitation or any major treatment. These FWD deflection values were used for evaluating the pavement strength during the case studies. There was a recent programme to evaluate the road networks in New Zealand using the traffic speed deflectometer. It uses Doppler radars to measure the reflected vibrations for evaluating the pavement strength and also to use for crack detection, geospatial assessment, imaging and laser profiling (NZTA, 2016). The differences between the emitted and reflected sound waves of different road sections indicate the relative differences in strength, material quality and moisture contents. Once the results of the traffic speed deflectometer tests are populated, it is expected that the deflection measurements can be used to develop the longitudinal profile of the road pavements based on strength and moisture conditions. These longitudinal profiles of the road sections can be used to validate the longitudinal risk rating developed through the MDRA as presented in Chapter 8 of the thesis.

10.3 Recommendations for Further Work

The MDRA framework developed in course of the research is complete and has been tested for its reliability and applicability in drainage needs assessment of the road network. Therefore, the framework has been suggested for implementation in any road network in New Zealand. The procedure for drainage risk assessment presented in the MDRA framework can be successfully applied for prioritising the road sections for proactive drainage improvement works. In addition, the development of a drainage risk profile based on the risk assessment (MDRA) has been demonstrated in this thesis and can be implemented in any road network in any road network in New Zealand. The research can be extended through the practical application of the framework in other road networks. In that case, the research focus should be on identifying the relevant moisture damage factors and their weights based on the effect of these factors on pavement failure.

The MDRA can be developed as a commercial tool using sophisticated programming languages. The tool can be implemented in any road network. The moisture damage parameter database (100 m road section) needs to be entered once in the tool. Most of the moisture damage parameter data can be obtained from the road asset management database. There can be a link between the risk assessment tool and the databases. Then the tool can yield and update the moisture damage or drainage risk profile of the network within the least effort and time. The methodology developed and demonstrated in the thesis can be used as the basis for any such risk assessment tool (software package).

The research could be extended to evaluate the performance of MDRA by drainage improvement. It is feasible to identify the effect of drainage improvement on road pavement performance. The process would be to install or improve drainage measures at alternative 100 m road sections in the site. The difference in pavement performance of different road sections (with or without drainage) can demonstrate the performances of drainage in reducing the failure risk of the road section. Long term monitoring of the road sections would help in comparing the performances of road pavements due to drainage improvement.

The risk assessment framework was developed as a tool for practitioners to use in developing the drainage FWP. The FWP for pavement renewal and resurfacing is mostly developed through deterioration modelling, especially for flexible granular pavements in New Zealand. There are a few tools available for developing the drainage FWP, especially to identify road sections for drainage improvement. Here the drainage improvement includes, but is not limited to, the installation of sub-soil drains, surface drainage (kerb and channel), reforming unlined water channels and high lip removal. The MDRA was conceptualised as an easy, hands on tool that can utilise the readily available data (FWD and other tests), video or physical inspections in assessing the road network and developing a profile based on drainage risk rating. The drive is to invest more in drainage improvement to increase the life cycle of the road pavement, and thus reduce the quantity of pavement preservation activities (pavement renewal and resurfacing).

Drainage improvement is considered as a proactive measure to reduce the risk of failure due to excess moisture in the road pavement. It could be possible to install drainage in some of the higher risk sites (MDRA) and monitor their performance in reducing the risk of failure. Some control road sections can be established without drainage and the rest of the sections can have the required drainage measures. Then the differences of the pavement conditions (distresses) and maintenance activities between the two groups of road pavements can be monitored. The real time measurement of moisture in the pavement using the time domain reflectometer probe (Hussain et al., 2011) would definitely help in differentiating the performances of the drainage measures in reducing the moisture among these two groups of road pavements.

In addition to drainage improvement, it is possible to evaluate the moisture susceptibility of different pavement materials in the road pavement and correlate it with the prediction of the MDRA. Material quality plays an important role in the performance of granular road pavements, especially to counter the adverse effect of excess moisture (Ekblad & Isacsson, 2006). In relation to this, MDRA has included pavement material quality, excess fines (High PI) and sensitivity of the subgrade as the moisture damage parameters. Different granular materials have variable capacities to counteract the adverse effect of excess moisture. There were efforts to evaluate the effects and performance of different granular materials in the presence of excess moisture (Amiri et al., 2010; Hussain et al. 2011). The drainage factors have a significant impact on the overall risk rating of the road section and it is possible to reduce the extent of the moisture damage through improving the moisture damage susceptibility of the road pavement as well. In this respect, a number of road pavements and surface materials can be trialled using 100 m road section. These trial roads need to be monitored for strength (using FWD), variation of moisture in wet and dry seasons and their pavement distress. This would help in identifying the correlation between the MDRA prediction and the pavement material's quality of a specific road network. This type of correlation, between the MDRA prediction and the moisture damage parameters could be undertaken using data from the LTPP road sections in New Zealand. However, the LTPP programme includes road sections from all parts of the country, where the MDRA is applicable for a specific road network. Therefore, the research suggests for the strategy to evaluate the long term performances of trial road sections in the network to develop the correlation with the MDRA prediction.

Overall the research is an effort to accommodate the concept of risk analysis in drainage needs assessment of a road network. The risk assessment framework (MDRA) has been developed as a practical tool through different stages in the research. Expert judgment has the key role in drainage needs assessment through the MDRA framework. The relevance of MDRA in detecting the drainage deficiency, and subsequently to prioritise the drainage improvement works in a road network, has been presented in a number of case studies in the thesis. Further research on quantifying the reliability and applicability of the framework in drainage needs assessment will increase its relevance in road network maintenance.

11 Appendices:

Appendix A

Inference Rules of the Fuzzy Logic Model

No	G_Risk	P_Risk	S_Risk	DRN_Risk	MD_Risk
1	Low	Low	Low	Low	Very Low
2	Low	Low	Low	Moderate	Low
3	Low	Low	Low	High	Moderate
4	Low	Low	Moderate	Low	Low
5	Low	Low	Moderate	Moderate	Moderate
6	Low	Low	Moderate	High	High
7	Low	Low	High	Low	Low
8	Low	Low	High	Moderate	Moderate
9	Low	Low	High	High	High
10	Low	Moderate	Low	Low	Low
11	Low	Moderate	Low	Moderate	Moderate
12	Low	Moderate	Low	High	High
13	Low	Moderate	Moderate	Low	Low
14	Low	Moderate	Moderate	Moderate	Moderate
15	Low	Moderate	Moderate	High	High
16	Low	Moderate	High	Low	Moderate
17	Low	Moderate	High	Moderate	High
18	Low	Moderate	High	High	Very High
19	Low	High	Low	Low	Low
20	Low	High	Low	Moderate	Moderate
21	Low	High	Low	High	High
22	Low	High	Moderate	Low	Moderate
23	Low	High	Moderate	Moderate	High
24	Low	High	Moderate	High	Very High
25	Low	High	High	Low	Moderate
26	Low	High	High	Moderate	High
27	Low	High	High	High	Very High
28	Moderate	Low	Low	Low	Low
29	Moderate	Low	Low	Moderate	Moderate
30	Moderate	Low	Low	High	High

No	G_Risk	P_Risk	S_Risk	DRN_Risk	MD_Risk
31	Moderate	Low	Moderate	Low	Moderate
32	Moderate	Low	Moderate	Moderate	High
33	Moderate	Low	Moderate	High	Very High
34	Moderate	Low	High	Low	Moderate
35	Moderate	Low	High	Moderate	High
36	Moderate	Low	High	High	Very High
37	Moderate	High	Low	Low	Moderate
38	Moderate	High	Low	Moderate	High
39	Moderate	High	Low	High	Very High
40	Moderate	High	Moderate	Low	Moderate
41	Moderate	High	Moderate	Moderate	High
42	Moderate	High	Moderate	High	Very High
43	Moderate	High	High	Low	Moderate
44	Moderate	High	High	Moderate	High
45	Moderate	High	High	High	Very High
46	Moderate	High	Low	Low	Moderate
47	Moderate	High	Low	Moderate	High
48	Moderate	High	Low	High	Very High
49	Moderate	High	Moderate	Low	Moderate
50	Moderate	High	Moderate	Moderate	High
51	Moderate	High	Moderate	High	Very High
52	Moderate	High	High	Low	High
53	Moderate	High	High	Moderate	High
54	Moderate	High	High	High	Very High
55	High	Low	Low	Low	Low
56	High	Low	Low	Moderate	Moderate
57	High	Low	Low	High	High
58	High	Low	Moderate	Low	Moderate
59	High	Low	Moderate	Moderate	High
60	High	Low	Moderate	High	Very High
61	High	Low	High	Low	High
62	High	Low	High	Moderate	High
63	High	Low	High	High	Very High
64	High	Moderate	Low	Low	Moderate
65	High	Moderate	Low	Moderate	High
66	High	Moderate	Low	High	High
67	High	Moderate	Moderate	Low	Moderate

No	G_Risk	P_Risk	S_Risk	DRN_Risk	MD_Risk
68	High	Moderate	Moderate	Moderate	High
69	High	Moderate	Moderate	High	High
70	High	Moderate	High	Low	Moderate
71	High	Moderate	High	Moderate	High
72	High	Moderate	High	High	High
73	High	High	High	Low	Moderate
74	High	High	Low	Moderate	High
75	High	High	Low	High	High
76	High	High	Moderate	Low	Moderate
77	High	High	Moderate	Moderate	High
78	High	High	Moderate	High	Very High
79	High	High	High	Low	High
80	High	High	High	Moderate	Very High
81	High	High	High	High	Very High

Appendix B

Inference Rules of the Fuzzy Logic Model (Revised)

No	Geophysical	Pavement Profile	Road Class and Pavement Strength	Drainage & Weather & Shoulder	Moisture Damage Risk (MDR)
1	Low	Low	Low	Low	Moderate
2	Low	High	Low	Low	Moderate
3	High	Low	Low	Low	Moderate
4	High	High	Low	Low	High
5	Low	Low	High	Low	Moderate
6	Low	Low	Low	High	Moderate
7	Low	Low	High	High	High
8	Low	Low	Very High	Very High	Very High
9	High	Low	Very High	Very High	Very High
10	High	High	Very High	Very High	Very High
11	High	High	Very High	High	Very High
12	High	High	High	Very High	Very High
13	Low	High	High	Low	High
14	Low	High	Low	High	High
15	High	Low	High	Low	High
16	High	Low	Low	High	High
17	Low	Low	Very High	Low	High
18	Low	Low	Low	Very High	High
19	High	High	Very High	Low	Very High
20	High	High	Low	Very High	Very High
21	Low	High	Very High	Very High	Very High
22	Low	High	Very High	Very High	Very High
23	Low	High	Very High	High	High
24	Low	High	High	Very High	High
25	Low	High	Low	Very High	High
26	Low	High	Low	High	High

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