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Application of Fuzzy Logic Based Risk Analysis to Identify the Moisture Damage Potential in Flexible Road Pavements

Mohammad N. U. Mia [1+], Theunis F. P. Henning [1], Seosamh B. Costello [1], and Glenn Foster [2]

Abstract: A fuzzy logic based risk analysis model has been developed to identify and evaluate the moisture damage potential in flexible road pavements. Long term field investigations in a New Zealand road network coupled with a review of the available literature helped in identifying the possible factors that may induce moisture damage in road pavements. An inference rule (If-Then) based risk analysis model has been developed. Expert knowledge and judgment were canvassed for setting up the membership functions for the inputs and the inference rules of the model. The model has been utilized in identifying and assessing the moisture damage risk of a number of road sections in the network. Further research will identify the correlation between the moisture damage risk and pavement distresses (rutting, roughness, flushing). This will be helpful in validating the proposed risk analysis model.

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***Key words**: Drainage need; Flexible road pavements; Moisture damage; Risk analysis.*

Introduction

Moisture related damage is one of the main deteriorating factors of road pavements. In New Zealand the majority of the road network is composed of either bound or unbound granular flexible pavements. These pavements consist of granular base course, treated with either cement, lime, or foamed bitumen. The function of the base course is to transmit the traffic loading to the subgrade without deformation [1]. A chip seal surface is provided to inhibit infiltration of water into the pavement and to ensure the required surface texture. Since most seals are not completely water tight, water still enters through the chip seal surface both under static and dynamic conditions. Consequently, the base course layer is designed to drain the water from the pavement formation. However, in situations where the base course is saturated; the moisture is trapped usually due to inadequate drainage. If the ground water table is high and the sensitive subgrade materials react in the presence of the moisture, then the road pavement performs poorly and shows symptoms of moisture damage. This situation is often worsened in combination with the heavy traffic loading of commercial vehicles [2-4]. So moisture damage is often critical and a predictive framework can identify the risk of premature failure and predict the need for drainage improvement.

Objective and Scope of the Research

The objective of this study is to develop and implement a risk analysis model as part of the conceptual risk assessment methodology for identification of moisture damage potential in flexible road pavements. The model is one of the candidate risk analysis techniques of the Moisture Damage Risk Assessment (MDRA) methodology that is presented in Mia et al. [5]. The MDRA is expected to be helpful for the 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 [6]. The topography of the region varies significantly, and has therefore been considered as one of the factors contributing to moisture damage in the road pavements.

Risk Principles in Road Asset Management:

Risk is defined as the amalgamation of the possibility and consequences of incidents that might hamper the desired objectives of a project or 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 [7].

In construction and project management, risk analysis is applied to identify the uncertainty and the consequences of the risk [8-9]. Road network management is a continuous program and the road controlling authorities need to be aware of the ongoing risks and have to take proactive actions to mitigate them. The scenario is often complex in a road network managed under a Performance Based Contract (PBC). The contractor has to manage the road network on a lump-sum cost usually for the medium to long term (10 years) and therefore has to bear the major risks associated with the network management [10]. Consequently, the risk assessment is often crucial for a PBC network both at the bidding and implementation stage of the contract.

[1] Department of Civil and Environmental Engineering, The University of Auckland, Auckland, New Zealand.

[2] Transfield Services Ltd.

[+] Corresponding Author: E-mail mmia013@aucklanduni.ac.nz

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In general, 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 Fig. 1.

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, identifying, analyzing and evaluating the risks. Often, these tasks require extensive knowledge and expert judgment, especially to identify the hazards or factors and their associated risks. However, the NZTA risk management framework is more suitable for project and traditional road maintenance contract management [7]

Application of Fuzzy Logic Model in Risk Assessment

Fuzzy set theories were first proposed by Lukasiewicz in the 1920s and were further developed by Zadeh in the 1960s. They developed the fuzzy set theories, based on the application of possibility theory into the mathematical logic system. Zadeh [11] 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. Fuzzy set theories are different from the classical set theories which states that an object either belongs to a set or not. The subjective judgment of the human mind and decision making process are variable and often involve uncertainty and vague linguistic expressions. The fuzzy set theories can be incorporated to formally define these linguistic terms such as low risk, close to or good conditions, through membership functions and utilize them for risk or opportunity assessment [11-12].

The risk analysis 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 the project [12-13]. The Table 1 summarizes the studies from the literature where the fuzzy logic model has been adopted for risk analysis in different sectors.

The scope of the fuzzy logic model in risk assessment is wide and focused towards the utilization of knowledge and expertise of the stakeholders. To date, it has been widely utilized in environmental,

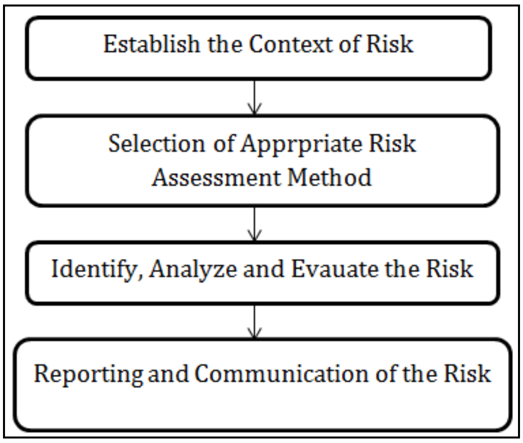


Fig. 1. Key Elements of Risk Management Process [7]

construction, project, and channel safety risk assessment as discussed in this paper. However, the application of fuzzy logic models in road asset management is limited with one study [16] showing the development of pavement condition assessment based on expert judgment and analytic hierarchy process.

Methodology

The detailed methodology for the development of the risk assessment framework has been presented in Mia et al. [5]. The sites were selected 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 model was developed and implemented in three stages, as presented in Fig. 2.

Stage 1:

Comprehensive literature review and field investigations were conducted to identify the possible factors of moisture damage in road pavement. In the course of that, a risk assessment methodology (MDRA) was conceptualized and is presented in Fig. 3.

The framework of MDRA includes a preliminary survey and assessment of the expert's knowledge to identify the risk scenarios and related factors. The next step was to adopt risk analysis techniques. Three candidate risk analysis techniques were proposed. The fuzzy logic model is one of the conceptualized risk analysis techniques and a vital part of the MDRA (Fig. 3). So the tasks of the stage 1 are mostly completed within the initial phase of the research and had been widely presented for feedback and consultations [5, 18].

Stage 2:

In this stage a generic fuzzy logic based risk analysis model was developed using the MATLAB program. The basic steps followed to develop the risk analysis model were;

a. Define the input and output of the moisture damage risk analysis techniques.
b. Define the membership functions for the input and the output
c. Develop the inference rules based on the engineering judgment
d. Analyze and simulate the output of the risk analysis.

The risk analysis model was developed in MATLAB program, used the Mamadani logic based inference system. The development of the model is further elaborated in the following sections where the generic model is presented.

The generic risk analysis model was developed based on the identified factors from a previous study [5]. Comprehensive judgment was incorporated into the study. The case studies were conducted in sixty road sections in the road network. The road network has been managed by the same organization for the last 15 years. They have developed vast knowledge and experiences about the network. 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

Table 1. Application of Fuzzy Logic Model in Risk Analysis.

Areas and Scope of the Research	Study
Environmental Risk	
The fuzzy logic model was as a hierarchical approach to identify the environmental risk of the south-west region of Bulgaria. Landslides, mud-rock flows, floods and seismic hazards were used as the inputs and the output is the complex natural risk. In the model the inputs were categorized as low, middle and high and presented in the interval (1, 10) by the trapezoidal membership function. The output was presented by the 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 and efficiently incorporated the knowledge and experiences of experts in risk assessment.	Zlateva Pashova [14]
Channel Safety	
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 was the basic output of the risk assessment and is presented linguistically as secure, basic security, and more insecure, unsafe and very unsafe. A triangular membership function in the scale of 1 to 10 was 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 [15]
Maintenance Planning	
A pavement condition assessment method was developed based on expert judgment using the fuzzy logic model and the analytic hierarchy process. 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 for the 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 weighted cumulative index’.	Sun and Gu [16]
Underground Construction	
A risk assessment methodology for underground construction was developed. The fuzzy membership model presented in the study incorporated 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, Cho [17]

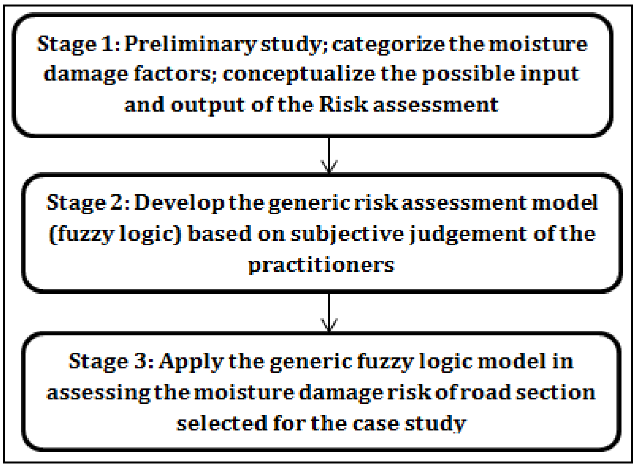


Fig. 2. Development Stages of the Risk Analysis Model.

to present the risk analysis model to the sponsoring organization. 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 requested to divide into groups to discuss the pros and cons of the model. The groups were requested to present their views and suggestions on the generic model. Overall the workshop was deemed successful and the feedback received was helpful in finalizing 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 analyzed 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 network is regularly inspected through physical and video survey. 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. Fig. 4 shows the screenshot of a video file of a road section. The video files are easy to analyze because those can be scrutinized at various speeds and angles. These video files were efficiently used in road network inspections regularly for network performance assessment.

Description of the Road Network

New Zealand is a long (approximately 1500 km in north-south direction) and narrow (400 km in east-west direction) country about

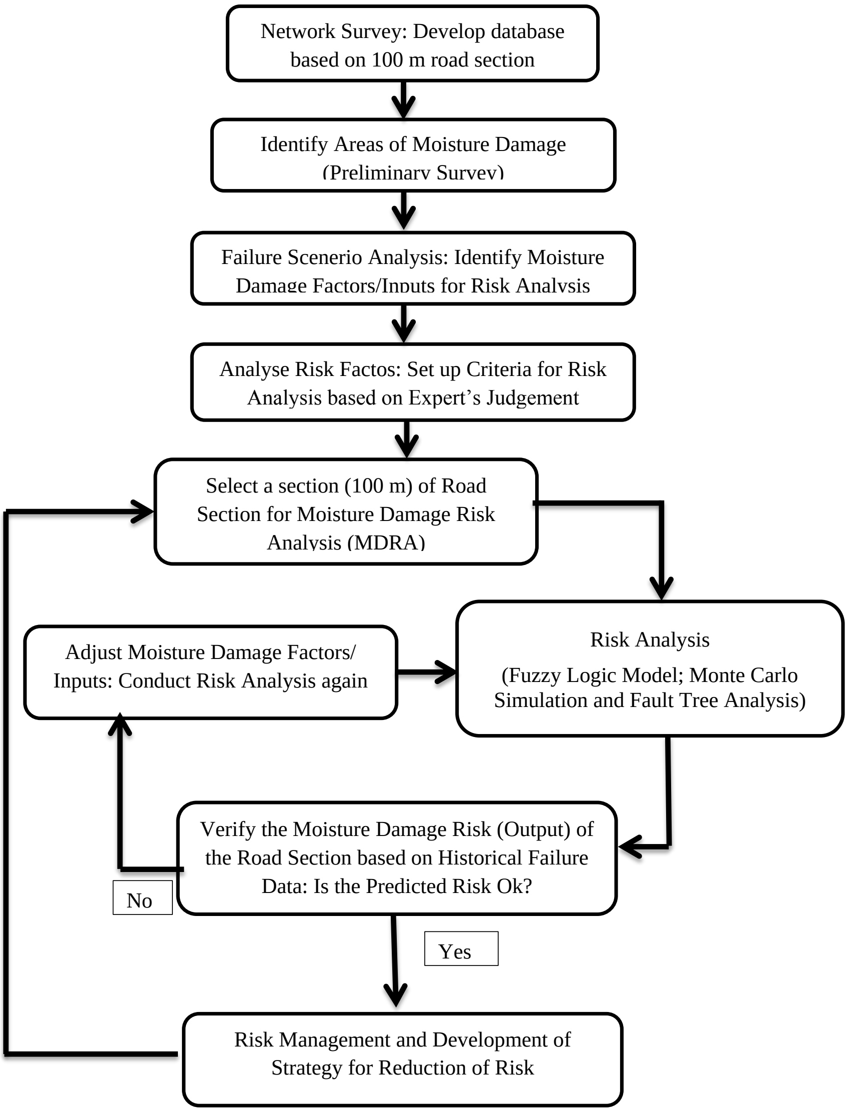


Fig. 3. Framework of MDRA [5].

Fig. 4. Screenshot of the Video of a Road Section.

268,000 km^2. 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 93000 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 [18-19].

The road network (West Waikato south) used for this study is in the north-west region of New Zealand. The Average Annual Daily Traffic (AADT) of the road network ranges approximately from 500 to 10000. The road pavements are predominantly chip seal with bounded (cement) granular base course. One tenth of the road network consists of stone mastic asphalt 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 belongs to moderate to high rainfall areas [6]. Weather and rainfall parameters may not vary significantly among the 100 m 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 to rugged hilly areas. Large portions of the road pavements in the network are constructed of cut and fill. In addition, major streams, including the country's longest river run across the road network. So the geophysical variations of the road network have notable effects on the proposed risk analysis model.

Fig. 5 and Table 2 gives the location and distribution of the West Waikato (South) network in New Zealand. The road network is divided into three sub-networks based on their classification and level of service. It has been managed under the Performance Specified Maintenance Contract (PSMC) since 1999, so the road networks are evaluated regularly based on the performance measures. The PSMC is a procurement model adopted in New Zealand for maintenance and management of a number of the state highway network. Under the PSMC contract, the provider has to maintain the road network for the long term (usually 10 years) at a lump-sum value and ensure to meet the predefined key performance standards [10, 20].

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 program. In part 2, the generic risk analysis technique is applied to identify the moisture damage risks of 100 road sections of ten different rehabilitation sites.

Part 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 [5]. The key challenges of developing the generic model are;

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

Moisture Damage Risk Factors (Input)

Table 2. Distribution of State Highways in Road Network [20].

Sub-net work	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

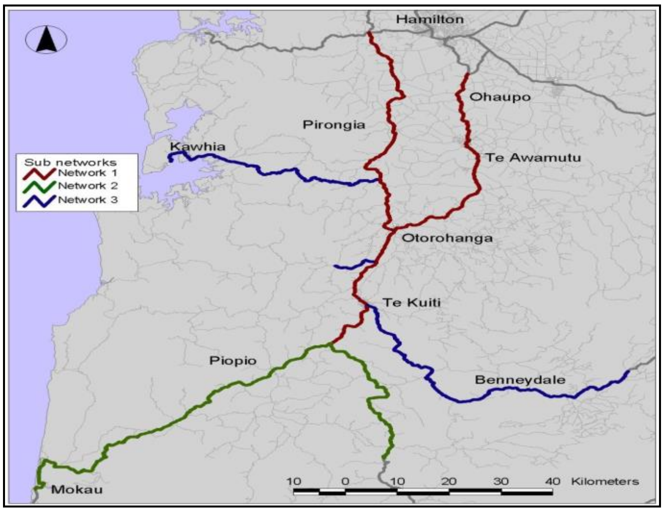


Fig. 5. West Waikato Road Network [20].

Usually pavement distresses like rutting, roughness, flushing, potholes, shoving and heaves are considered as signs of pavement failure [21]. However, these distress mechanisms are consequences of excessive moisture in the pavement formation. So 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 pavement formation. The factors responsible for pavement failure identified in some of the studies are presented in Table 3.

The factors identified during the preliminary study included in Fig. 6, contributed to the varying degrees of moisture damage at different road sections. Here, the '% of Sites' indicates the fraction of the total road sections that possess an individual factor and among them the '% of MD Sites' is part (percentage) of the fraction that shows symptoms of moisture damage. The road sections with side hills and streams possess more symptoms of moisture damage compared to the road at rolling round and 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 generalized and categorized into two major groups for use as the inputs for the risk analysis. Table 4 contains four major categories of moisture damage factors, along with the root cause of failures. These factors have been developed based on the expert knowledge, experiences during the preliminary study, field work and a rigorous literature review. These factors can be modified based on the network characteristics and conditions of the maintenance management system.

The charts presented in Tables 4 and 5 will be used to identify the moisture damage factors for use in the risk analysis. Each road section was scrutinized using the chart in Table 4. Each count of the presence of the root causes in Table 4 of a road section generated a trigger. The extent (linguistic expression of the factors) of the moisture damage factors (input) was identified based on the total

Table 3. 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 [21]. Water ingress, inadequate surface and sub-surface drainage, thin pavement layer, inadequate horizontal gradient, unsealed shoulder, high ground water table, excessive fines in aggregate, old pavement, excess plasticity, sharp curves, materials quality, construction quality have been considered as the root causes of the predominant failures in road pavement.	Schlotjes et al. [22]
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 included 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, Arampamoorthy [23]

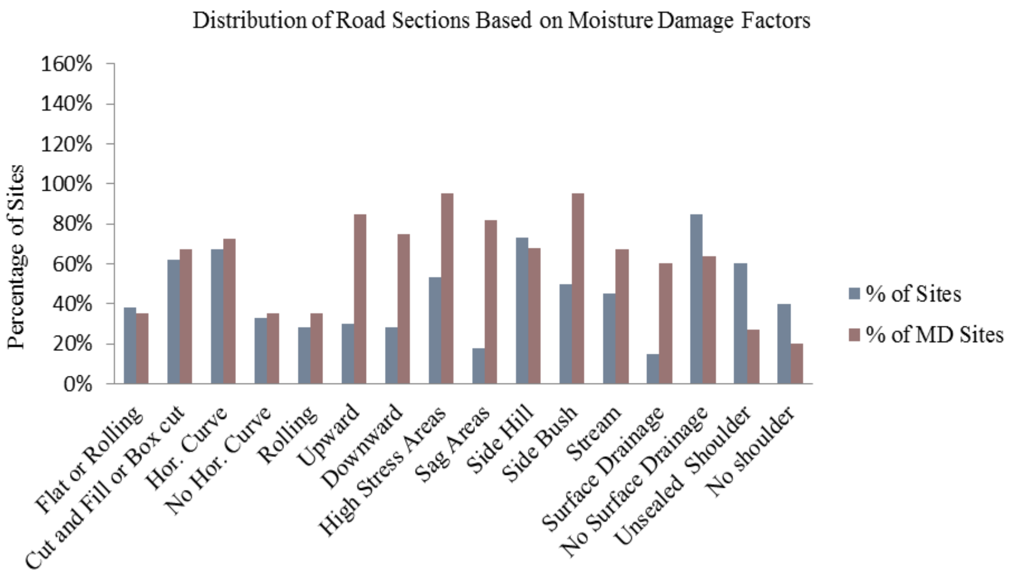


Fig. 6. Moisture Damage Factors Identified [5].

Table 4. Moisture Damage Factors and Inputs for Risk Analysis (Chart).

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) Section at vertical Sag
	P_Risk: Risk factors related to pavement profile and shoulder (Within the road pavement)	Topography (Flat, Rolling and Sloped terrain) Pavement construction (Cut and fill and Box cut) Inadequate Shoulder Sensitive subgrade
Dynamic	S_Risk: Risk factors related to materials and the strength of the road pavement DRN_Risk: Risk factors associated with drainage (surface and subsurface) , traffic, climate	Weak pavement layer Thin surfacing Old and deteriorated pavement and surfacing Materials with high PI/fines Cross fall (inadequate) Kerb and channel blocked, damaged Subsoil drain non-functional Rainfall high Water table high (1 m from ground level) Traffic volume high Heavy Commercial vehicle high

number of triggers as shown in Table 5. The moisture damage factors were expressed as low, moderate and high. The more the number of triggers, higher the extent of the risk factor. In the model, the trapezoidal membership functions were used to define the linguistic expressions (low, moderate and high) of risk factors. Similar trapezoidal membership functions (Column 5, Table 5) are used to express the moisture damage factors in the model. The parameters of the trapezoidal membership function are given in column 4 of the table. As the range of the risk rating is 0 to 10 so the parameters (-3) and (13) of the trapezoidal membership functions are obscured in the trapezoids in Table 5. The horizontal axis represents the input value for the risk analysis identified through the evaluation chart in Table 4. The vertical axis represents the degree of possibility on a scale of 0 to 1.

Inference Rules:

The Inference rules (IF-Then) were developed based on engineering judgment, 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 incorporated based on the valuable comments received at the workshop. A total of 81 inference rules used in the risk analysis model are presented in Appendix 1. The inference rules are network specific and would need to be adjusted or developed for use on another network.

Risk Analysis Model (Structure):

The generic structure of the fuzzy logic based risk analysis model is presented in Fig. 7. It uses the fuzzy inference system (Mamadani) in the Matlab program. 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.

Risk Analysis Model (Output):

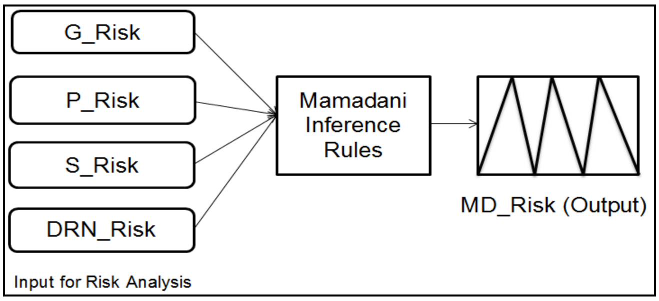


Fig. 7. Structure of the Risk Analysis Model (Input-Inference rules-Output).

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 [7]. 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 [24]. The New Zealand road safety assessment program (KiwiRAP) uses low, low to medium, medium, medium to high and high to describe the crash risks based on collective and personal risk factors [25]. 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 by membership function (Mamadani) or by constant (Sugeno) values. For this research, The MD_Risk is formulated to provide a rating on the scale of (1-10) by the triangular membership function as presented in Table 6. 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 a road section. The simulated outcome of the risk analysis model is either the rule viewer (Fig. 8) or the three dimensional surface viewer (Fig. 8).

The rule viewer (Fig. 8) is the typical simulation output that will be used for risk analysis in the case study. There are 81 inference rules adopted in the risk analysis model. Each horizontal line in

Table 5. Moisture Damage Factors and Related Membership Function/Parameter.

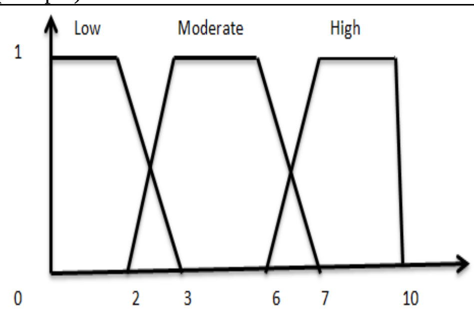
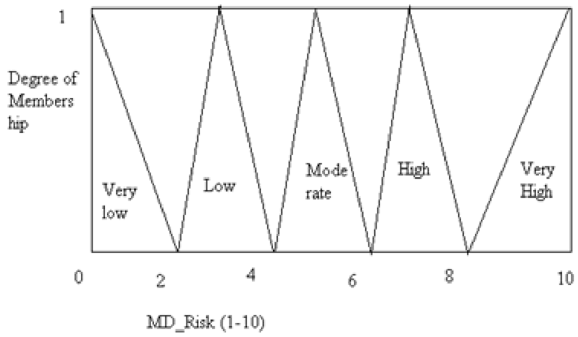
Moisture Damage Factors	Linguistic Expression	No of triggers (Table 4)	Parameters of the Membership Function	Membership Function of G_Risk (Sample)
	Low	0-1	[-3, 0, 1, 3]	
G_Risk	Moderate	2-3	[2, 3, 6, 7]	
	High	> 3	[6, 7, 10, 13]	
	Low	0-1		
P_Risk	Moderate	2-3	Same as Above	
	High	> 3		
	Low	0-1		
S_Risk	Moderate	2-3	Same as Above	
	High	> 3		
	Low	0-1		
DRN_Risk	Moderate	2-3	Same as Above	
	High	> 3		

Table 6. MD_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%	

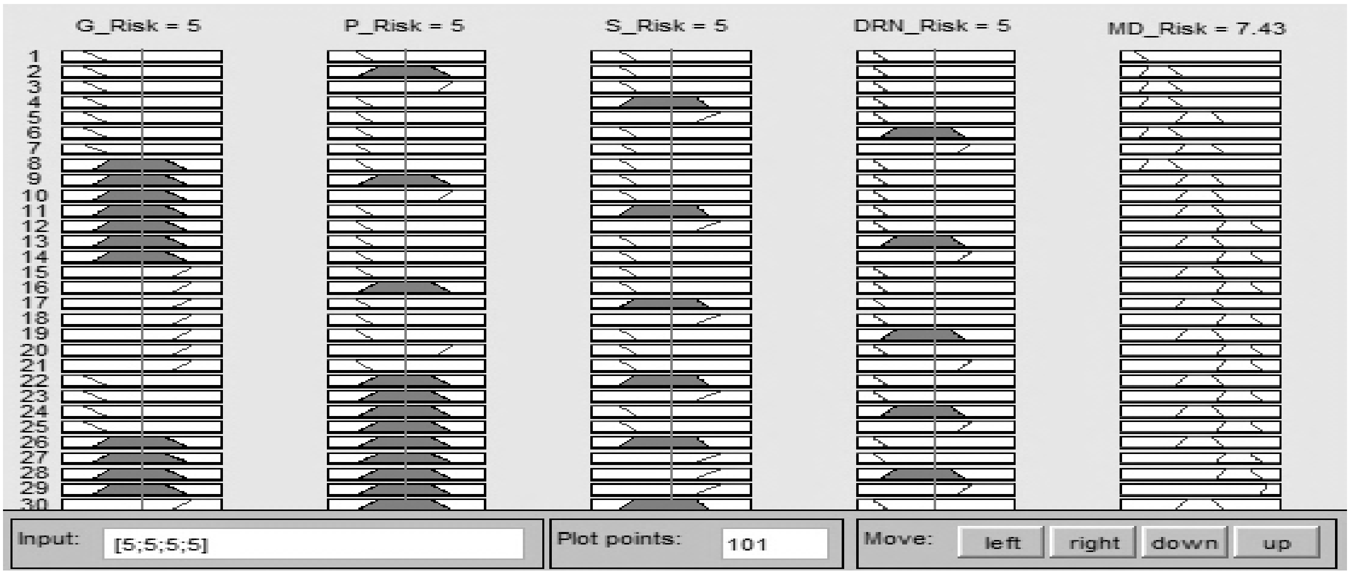


Fig. 8. MD Risk Output (Rule Viewer) of the Fuzzy Logic Model.

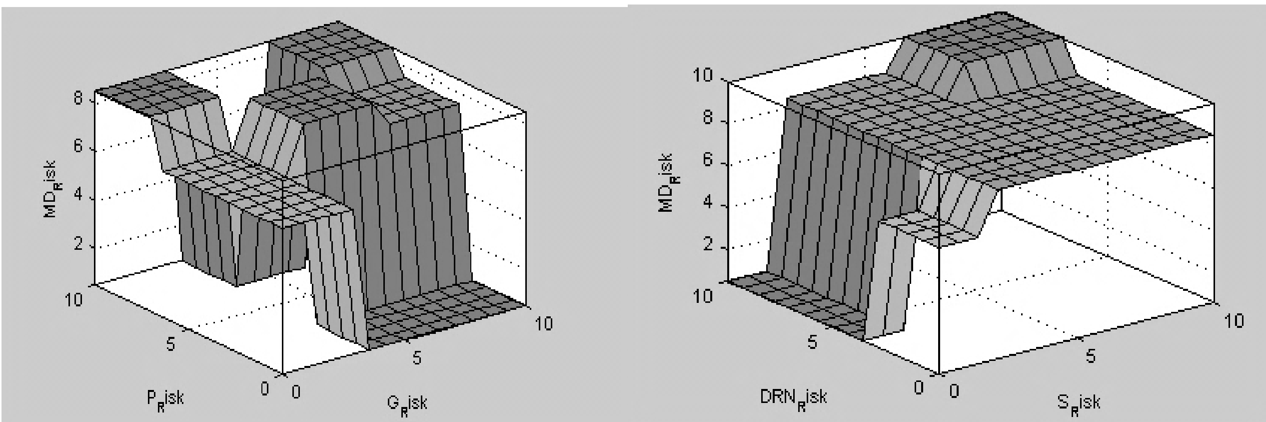


Fig. 9. MD_Risk Output (Surface View) of G_Risk vs. P_Risk (Left) and DRN_Risk vs. S_Risk (Right).

Fig. 8 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) %.

The surface viewer (Fig. 9) 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 (Fig. 9, left). The other two factors

(DRN_Risk and S_Risk) were found to be plotted in two horizontal axes, whereas the MD_Risk based on these two factors were in the vertical axis. This surface viewer is more applicable for graphical representation of the moisture damage factors and MD_Risk of the model.

Part 2: 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 of different sites in the network. The database of road sections used in the preliminary study [5] 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, 100 road sections were analyzed to predict the moisture damage risk. Each site was scrutinized through the risk analysis model. Fig. 10 shows the variation of MD_Risk (output) and the moisture damage factors (inputs) of 13 road sections of one site in the case study.

Moisture damage factors (inputs) of thirteen road sections have been plotted along with the MD_ Risk (Output). The vertical axis is the MD_ Risk rating and the horizontal axis presents 13 road sections' number. 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_Risks of the road sections followed a similar pattern of the moisture damage factors (G_ and P_Risk). The distribution of the simulated outcome of the risk analysis model (MD_Risk) of 100 road sections is presented in Fig. 11.

In Fig. 11, 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 section of each of the MD_Risk categories has been plotted as well. The MD_Risks 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 section has been identified to be at very high risk. These road sections analyzed for the study will be under close scrutiny and monitored in the future to identify their actual performance both in dry and wet weather conditions. Here performance indicators such as rutting, roughness, flushing, and texture of the road sections will be monitored at regular intervals. MD_Risks obtained from the risk analysis model and the average lane rutting of a number of road sections of a particular site were plotted in Fig. 12.

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 subgrade layer [1]. The average lane rutting of 100 m road sections of a site, were plotted against their predicted MD_Risk (Fig. 12). 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.

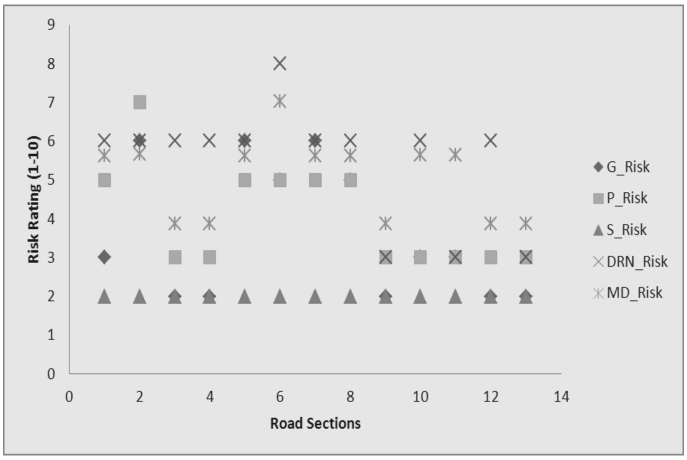


Fig. 10. Distributions of Risk Factors and MD_Risk.

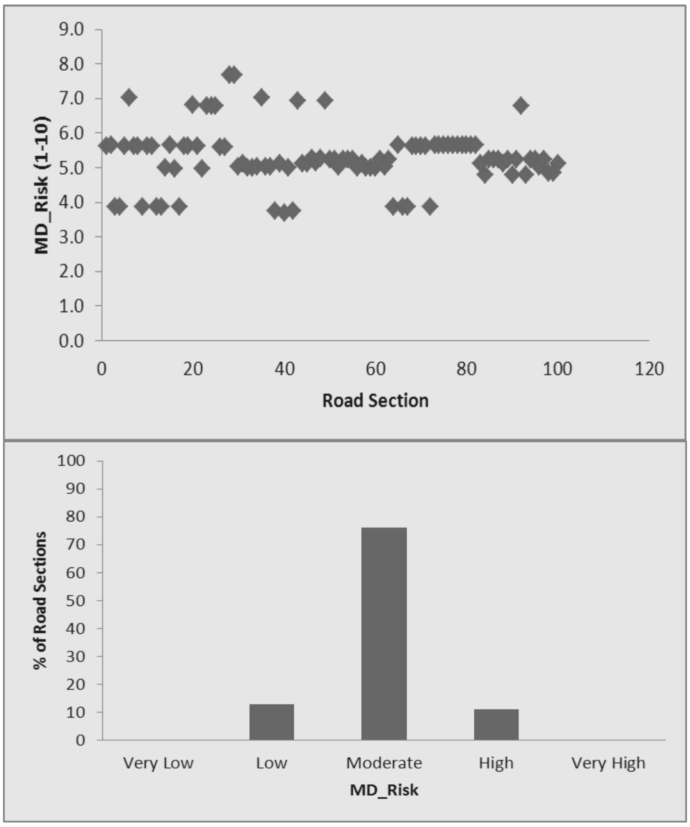


Fig. 11. Distribution of MD_Risk of the Road Section**.**

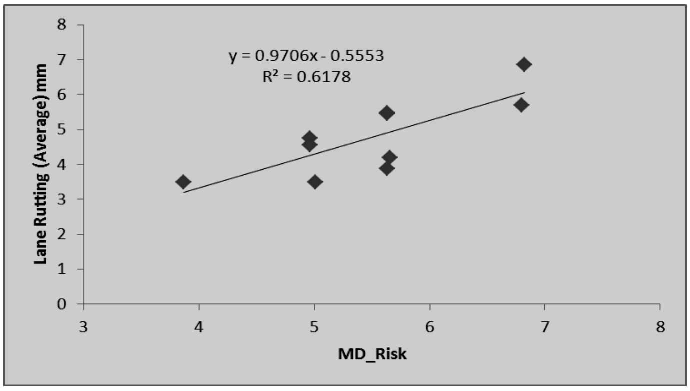


Fig. 12. Correlation of lane Rutting and MD_Risk of a Site**.**

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 presented in Mia et al [5].

Conclusions

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 the reduction of the level of service of the road pavements. The damage caused by moisture in road pavements has some severe consequences. Among them expensive renewal, heavy maintenance, wet road crashes, injuries and fatalities are notable to mention. These consequences are often considered as the risks for the road controlling authorities. Now, these risks are partially transferred to the contractors or management organizations, especially in the long term performance based contracts. So the contractors have to be proactive in predicting the major risks, including the moisture damage in the road network. In this regard, a moisture damage risk assessment method [26] 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 (Mamadani) 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 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 and accommodated to use 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 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. There is scope to develop fuzzy logic based prediction models to identify the road sections that are at risk of pavement distresses like rutting, shear and cracking failure. The factors responsible for these pavement distresses have to be identified based on the long term forensic investigations and field evaluation. The road controlling authorities can adopt proactive measures, especially the drainage improvement, pavement profile correction, resurfacing and rehabilitation based on the MDRA model. The model will be validated through long term evaluation of the performance indicators of road pavements. Although the risk analysis model is network specific, it can be utilized for other road networks with sufficient adjustments of membership functions and inference rules.

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Appendix 1. Inference Rules (If-Then) of 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
31	Moderate	Low	Moderate	Low	Moderate
32	Moderate	Low	Moderate	Moderate	High
33	Moderate	Low	Moderate	High	Very High

Appendix 1. (Continued)

No	G_Risk	P_Risk	S_Risk	DRN_Risk	MD_Risk
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
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