

# Fault Tree Analysis and Risk Assessment of Unbound Granular Pavement Material Performance

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## ABSTRACT

This paper describes the methodology issues considered in using Fault Tree Analysis to develop a risk assessment tool for unbound granular pavement material performance in Queensland. Example results from the tool are also presented. Granular pavements form a major geotechnical asset for Queensland Department of Main Roads (QDMR), and material underperformance is a significant concern. The uncertainty and economic consequences surrounding underperformance of granular pavements make them a prime candidate for structured risk assessment. The model was built using GoldSim, a simulation program that allows modelling of complex systems and quantitative probabilistic simulation. GoldSim is used to model a Fault Tree describing pavement performance factors and possible failure modes. The model uses semi-quantitative input ratings to describe the project scenario and the consequences for each failure mode, and outputs semi quantitative risk rankings for each failure mode. The model provides a relative measure of risk and is useful for comparing project scenarios and identifying high-risk areas for specific scenarios. The paper presents the model outputs for a particular scenario and compares them against actual performance.

## 1.0 INTRODUCTION

### 1.1 Risk in Main Roads

Queensland Main Roads are responsible for the construction, maintenance and administration of Queensland's most valuable physical asset: the state road network. It has a replacement value of about \$23 billion. The majority of roads administered by Main Roads are unbound granular pavements, forming a major geotechnical asset for Main Roads.

Pavement materials have a significant effect on pavement performance. Material problems generally have a disproportionate effect on the cost and performance of a project. Material failures are often significant in pavement underperformance [Wijeyakulasuriya, Ramanujam et al 2003(1), QDMR 2003 (2)].

The interaction of material source parameters, moisture sensitivity, and production and construction effects make material performance very complex. The combination of poor understanding of material properties, non-standard materials and water create a risky situation [Atkinson 1999 (3)].

Other issues that have contributed towards a poor appreciation of material performance risks include:

- Pavement loadings and design responsibilities are increasing, while budgets are shrinking [QDMR 2003 (2), Richmond 2003 (4), Skinner 2002 (5)].

- Design resources do not characterise pavement materials performance risks well [Wijeyakulasuriya, Ramanujam et al 2003 (1), QDMR 2003 (2)].
- Current Main Roads risk assessment tools are designed to analyse diverse risks associated with project management, not specific performance risks.

These issues increase the risk of pavement underperformance due to material issues. This creates a need for some method suitable for managing and assessing these risks.

### 1.2 Pavement Performance

Poor pavement material performance manifests through different failure modes. Failure modes fall into two different groups: structural integrity, and functional performance. The distinction between failure types is relevant when considering the consequences of different failures.

Functional failures have cost, comfort and safety consequences. Structural integrity is the ability of the pavement to withstand loads. Table 1 shows the failure modes considered in the pavement material performance model.

Table 1: Pavement Failure Modes

Structural Failure	Functional Failure
Distortion (rutting, shoving, heave)	Skid Resistance
Cracking (crocodile, age, longitudinal)	
Disintegration (potholes, edge defects)	

Poor performance of pavements can generate safety issues, costs to the travelling public and costs to the organisation. Reeves [2001 (11)] estimates that poor performance can be linked to at least \$25 million of Main Roads annual expenditure, due to premature failures, additional costs during construction and increased maintenance and rehabilitation costs.

Hunt's [2002 (10)] study of pavement performance shows that underperformance has risen within the last ten years. Based on pavement roughness (a measure of pavement distress), it showed that pavements built in the last twenty to thirty years are meeting their design lives more consistently than their younger counterparts (Figure 1). This trend is noted by Atkinson [1999 (3)].

## 2.1 Risk Identification

Risk identification needs to specify the most significant risks. This step takes apart the complex system that represents pavement material influence on pavement performance. The system is divided into failure modes, and the base causes of these failures.

### 2.1.1 Failure Modes

Poor performance of the pavement material has several different manifestations:

- Distortion
- Disintegration
- Cracking
- Punching (seal aggregate penetrating base)

(The distinction between structural and functional failures is only relevant for assigning consequences).

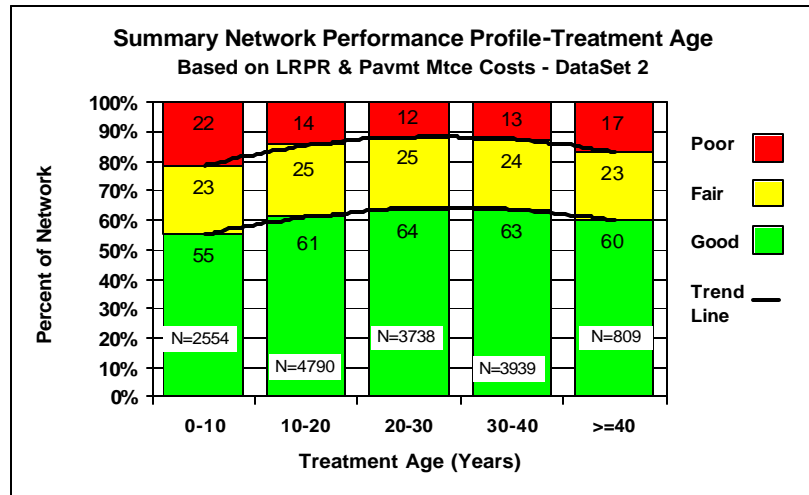


Figure 1: Pavement Performance [Hunt 2002 (10)]

## 2.0 RISK DEFINITIONS

**Risk** is the *chance* of something happening that will have an *impact* on objectives. It is measured in terms of *likelihood* and *consequence* [AS/NZS 4360 1999 (9)].

**Risk Management** is a systematic method of identifying, analysing, evaluating and controlling risks [AS/NZS 4360 1999 (9)]. It allows a more structured use of engineering judgement and experience in making decisions [Tsolakis, Thoresen et al 2002 (8)].

**Risk Assessment** is the overall process of risk analysis and risk evaluation. After identifying the important risks, a risk assessment tool helps analyse these risks to provide information to the risk evaluation.

### 2.1.2 Base Causes

The occurrence of these failure modes is controlled by a number of variables. These base causes have been grouped under the following headings in Table 2:

Table 2: Material Performance Factors

Performance Factor	Examples
Material Properties	Strength, reactivity, grading
Environmental Loads	Rainfall, temperature
Traffic Loads	Volume, % of heavy vehicles, growth
Cross Section	Drainage, layer thickness
Construction	Compaction, moisture
Maintenance	Reseal frequency, routine maintenance

## 2.2 Risk Analysis

Risk analysis aims to discriminate minor acceptable risks from major risks. The severity of a risk is determined by the relationship between likelihood and consequence [AS/NZS 4360 1999 (9)]. The risk analysis methodology controls both the way likelihoods and consequences are estimated, and how they are combined to estimate risk. Both of these must suit the risk problem and the user.

In this case, pavement material performance is a complex failure mode with many variables, so the analysis must be detailed enough to model this. The users will be Main Roads staff, who do not have the time, expertise or data to use sophisticated statistical models, so the risk assessment tool must also suit their resources.

### 2.2.1 Complex Failure Modes

The failure modes associated with poor pavement performance are complex, involving many different factors and interrelating subsystems. An example of this is the interaction between material properties and water. This is critical to the performance of the pavement, but both of these elements are dependent on many other factors, such as construction, climate, material production and material source properties.

The complex failure modes that pavements display have many component events occurring in sequence. Evaluating complex failure modes requires breaking these sequences down. The risk analysis method must be able to account for the interaction of these variables.

Current risk assessment tools in Main Roads are based on qualitative risk matrices. This is an inductive method, and is concerned with what types of failures are possible – *what may arise from a particular initiating event*. These methods are good for broad-brush risk assessments and overviews.

But simple overview methods lump together all the variables that affect an event's likelihood. This makes it difficult to judge the likelihood of events with many factors affecting their occurrence [Vick 2002 (12)].

More detailed examples of these methods, like Event Trees, are also difficult to apply to complex systems. This is because the different possibilities arising from subsystem failures (both singly and in combination) become too great [Vesely et al 1981 (13)].

These inductive methods produce many divergent paths, especially if many different factors are involved. For example, there are many different possible outcomes for a particular performance factor (causative agent) depending on how it combines with other performance factors. This makes a large, unwieldy event tree.

### 2.2.2 Analysis Method

The method of analysis defines how likelihood and consequence combine to form an estimate of risk, forming the framework for the analysis. Deductive methods focus on *how a specific failure can happen* (eg rutting). This allows the dissection of the failure process to examine the interaction of these factors, especially where event trees or other inductive methods would be unmanageably large [Vick 2002 (12), Vesely et al 1981 (13)].

Fault Tree Analysis has been selected as the most appropriate way of analysing a complex event such as pavement failure. Fault Trees identify the key failures, in this case pavement material failure. These key failures are broken down into chains of sub-failures until the base causes are reached (the performance factors).

The Fault Tree forms a logic map of the system components and the interaction of different variables to generate the major failure of interest. This forms the analysis framework for the calculation of likelihoods.

Each subsystem failure is linked by Boolean logic – AND (if all base causes apply) and OR gates (if any base cause applies). Fault trees are quantified using Equations (1) and (2):

$$\text{AND: } P_{\text{AND}} = P_1 \times P_{i+1} \times \dots \times P_N \quad (1)$$

$$\text{OR: } P_{\text{OR}} = 1 - (1 - P_1) \times (1 - P_{i+1}) \times \dots \times (1 - P_N) \quad (2)$$

These equations assume independence between the base causes (performance factors). The performance factors have been dissected to a reasonably detailed level to avoid too much dependence between base causes.

The user attaches probability estimates ( $P_i$ ) to the base performance factors, as these likelihoods are easier to judge than for complex failure modes. The fault tree calculates these likelihoods up the tree using Equations (1) and (2), to arrive at the overall probability of failure. The failure mode probabilities are then multiplied by the consequence of failure to get an estimate of risk. Figure 2 shows a major subsystem of the pavement material fault tree.

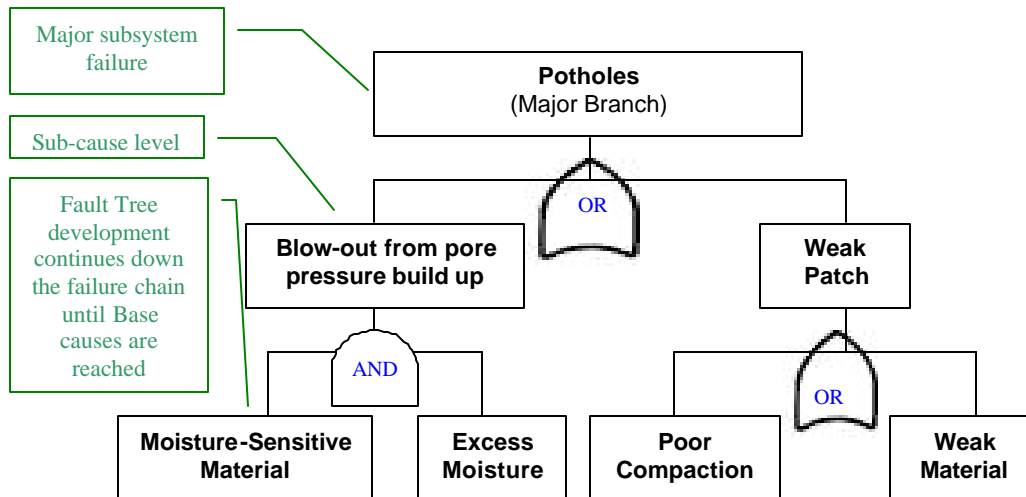


Figure 2: Example Segment of Pavement Material Performance Fault Tree

### 2.2.3 Expressing Probability and Consequences

This concerns the way estimates of likelihood and consequence are expressed. *Qualitative* descriptive methods are easy to use, but are difficult to apply in any detailed analysis of the failure process. *Quantitative* methods use numerical values to assess likelihood and consequence. However, it can be a difficult, data-hungry and expensive exercise to derive accurate numbers [Williams 1998 (14)].

The *semi-quantitative* approach allocates numbers to qualitative word rankings describing likelihood and consequence. These are a quantified expression of engineering judgment [Vick 2002 (12)].

The numerical conversions are based on a five point logarithmic scale, as per Williams' risk assessment model [Williams 2001 (15)]. These are shown in Table 3 below.

This avoids misinterpretation of numbers as probabilities, while also clearly discriminating between likelihood levels.

The semi-quantitative approach to risk analysis combines the flexibility, feasibility and ease of qualitative methods with the rigour and analytical advantages of quantitative methods.

The semi-quantitative inputs suit the analytical needs of the risk problem. It allows for numeric combination of many event likelihoods for analysis of the interactions between complex events and subsystems.

Semi-quantitative inputs also suit the tool's users. Main Roads staff do not have the time, expertise or data to produce statistical models. The semi-quantitative method suits the wealth of practical experience that characterises Main Roads staff. It allows staff to use practical experience and engineering judgement in a more structured way.

Table 3: Likelihood and Consequence Ratings

Likelihood		Log Scale	Consequence		Log Scale
Rating	Description		Rating	Description	
1. Rare	May occur	0.01	1. Negligible	Dealt with through routine maintenance, negligible expenditure	0.01
2. Unlikely	Could occur	0.033	2. Low	Threatens road's effectiveness, minor maintenance expenditure	0.033
3. Moderate	Moderate occurrence likelihood	0.1	3. Medium	Requires significant premature expenditure	0.1
4. Likely	Will probably occur	0.33	4. Severe	Threatens road performance, needs major premature maintenance	0.33
5. Almost Certain	Expected to occur	1	5. Extreme	Permanently harms road and requires premature rehabilitation	1

### 2.2.4 Modelling

The Fault Tree is modelled in GoldSim, a software package provided by Golder Associates Pty Ltd. Likelihood and consequence judgements are transferred from an Excel spreadsheet to the GoldSim model. GoldSim calculates the risk rankings for the scenario.

## 3.0 RESULTS

### 3.1 Example Outputs

The Fault Tree model aims to assist in ranking the relative severity of risks for each failure mode for unbound granular pavement materials. This can be used to compare the severity of different failure mode for a specific project scenario. This can isolate the major risks for that particular scenario, and identify where funds can best be directed to reduce the overall risk. The result format for each individual scenario is shown in Figure 3.

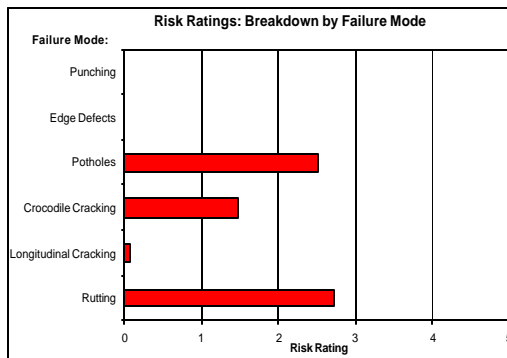


Figure 3: Risk Ranking

The risk for each failure mode can then be combined to give a global estimate of risk for the scenario. This is the cumulative risk for the scenarios, with the bar length reflecting the combined risk from each failure mode. Figure 4 compares scenarios where each performance factor is set to its extreme in turn. (All consequences were set to their extreme).

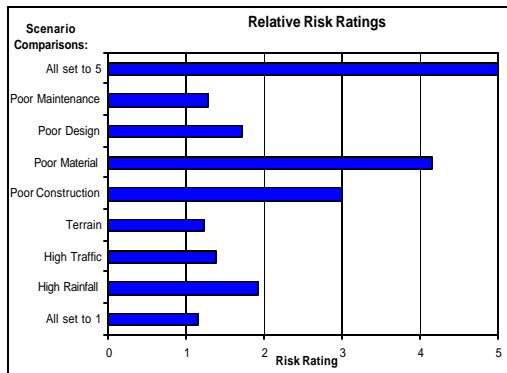


Figure 4: Risk Ranking Comparing Scenarios

## 3.2 Model Validation

The model is currently undergoing sensitivity testing, field testing and feedback from potential users. Part of the validation process has been comparing predicted to actual performance for different project scenarios.

A significant bypass project is used as an example here. The project featured a thick pavement with good quality material:

- strong (10% fines wet value = 340 kN)
- durable (degradation factor of 70)
- well graded and
- was crushed material with high densities

But the material had little or no plasticity, and the site suffered rainfall and the nuclear meters used for compaction control were poorly calibrated. Figure 5 shows that according to the model, this scenario has a high rutting risk and a medium risk rating for potholes.

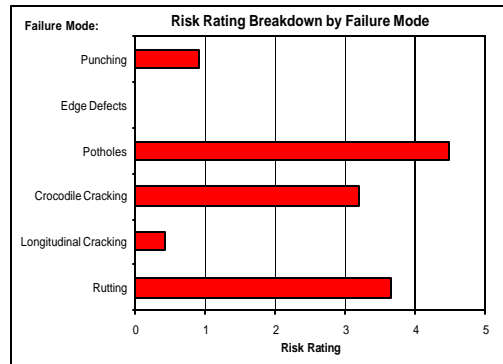


Figure 5: Risk Ranking for Test Scenario

The actual project suffered rutting and potholes before opening. Figure 6 shows Repeated Load Triaxial results for the material. High plastic strains are evident at the specified DoS limits, showing that this material was susceptible to rutting at these moistures.

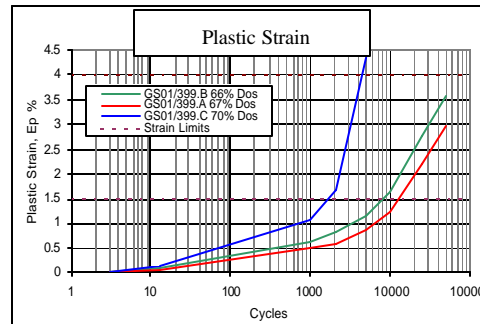


Figure 6: Plastic Strain for Test Scenario

These initial validation results indicate that the model gives a reasonable indication of high risk areas for pavement material related failures.

### 3.3 Model Limitations

Fault trees, like all models, are subject to the inaccuracies of modelling. These are generated by the assumptions and inaccuracies of representing a real, complex system in some logical virtual construct. But the sensitivity to model error can be minimised by using the model results for comparison studies, rather than using the absolute output to estimate risk.

The fault tree does not represent the entire system, only the area of interest to the analyst. The risk analysis is only valid for the failure modes that have been included in the fault tree, in this case, those associated with unbound granular pavement materials.

Any decision maker should beware of results that indicate very, very small probabilities of failure. This means that the system is unlikely to fail in the ways considered, but is far *more* likely to fail in ways that have not been considered.

### 4.0 CONCLUSIONS

The model shows that Fault Tree Analysis is a useful tool for risk analysis. It allows detailed examination of complex failures with many variables, such as unbound granular pavement material performance.

Semi-qualitative inputs are a flexible, powerful way of using engineering judgement to characterise likelihood and consequence.

The model provides individual risk rankings for different failure modes for a particular scenario. It can also be used to compare scenarios in terms of a global risk ranking. The model shows reasonable results so far, although model validation is still in progress.

The risk assessment tool will help designers consider the performance risks associated with pavement material. It is particularly appropriate for unbound granular materials as it allows the examination of failure modes that are not well covered in standard methods.

### 5.0 ACKNOWLEDGMENTS

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