# The Effect of Link Reliability on Benefit/Cost Ratios

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# Executive Summary

This report develops project evaluation procedures to incorporate risk assessment of road link reliabilities. When currently evaluating projects, the assumption generally made is that the existing network will continue to perform as it stands, with no closures. This does not consider the economic consequences of delays in reinstating closed links, or the relative importance of those links with few (or no) suitable alternative routes.

Recently there have been a number of research initiatives in New Zealand to examine the risk of link closure or degradation inherent in our existing road network. There is still a gap however for the development of procedures that can be incorporated into Transfund's *Project Evaluation Manual* (PEM). Having identified the various risks and costs, and with a number of potential mitigation projects available, a means of calculating the Benefit/Cost Ratio (BCR) for these projects is required.

The main objectives of this study were:

- To review the existing PEM procedures and recent research to identify areas where additional procedures may be useful.
- To develop calculations and procedures for the effect of link reliability.

This report summarises that work. It reviews the current Transfund evaluation procedures and recent work in this area. A discussion follows, suggesting directions from here. Simple link reliability theory is then developed, based on the previous literature, as well as typical examples of how this theory could be applied. The application of this theory within a project evaluation context is also considered.

The key findings of the study were:

- The PEM does not currently provide many evaluation tools relating to risk and reliability. Security of road access and impacts of projects on corridors and networks are only considered in the context of intangible benefits and descriptive details. No guidance is given on derivation of delay/detouring costs, nor specific examples given of link reliability. Arguably, this lack of evaluation tools is because most projects do not need to consider it in their evaluation, and it can be quite a specialised topic.
- There are two distinct phases in assessing network reliability. The first is a qualitative assessment of the hazards facing the existing road network, to identify which links appear most vulnerable to potential damage or closure, at a strategic level. The second is a quantitative evaluation of projects designed to improve the reliability of the existing road network. It is in the latter area that further detail and refinements could be provided in the PEM, for individual projects at least.
- The overall reliability of a highway link or network can be affected by projects involving construction of new links or the improvement of existing links. Improvement to a link could include improved reliability of a link under various hazards, or an increase in link capacity, either in terms of volume or vehicle restrictions. Improvements to alternative routes may also significantly benefit main strategic routes.
- For project evaluation, link reliability should be considered when the project is located on, or affects the reliability of, a strategic link, i.e. if there are two or fewer

alternative routes. Because of the extra work involved, the costs or benefits of the project should exceed a specified minimal level before this additional evaluation is undertaken.

Having established that link reliability is to be considered, the costs of closure for either the do-minimum (existing) or project option need to be calculated. Assessment of link reliability costs requires:

- estimations of likelihood and duration of closure events,
- traffic distributions across road links during normal and "closure" times,
- estimations of deferred or cancelled trips, and
- determinations of user costs as a result of these factors.

There may also be a change in physical restoration/maintenance costs (e.g. less likely to need reinstatement) that should also be evaluated.

Some draft procedures for incorporating the effects of link reliability into project evaluation are provided, using decision charts and worksheets. The worksheets are particularly designed for "simple" closure situations, i.e. where a project will affect the likelihood or impacts of closures to a single link. Some modification to the worksheets may be necessary to allow for more complex calculations of link reliability.

The next step is to apply these techniques in the evaluation of some projects (either already evaluated traditionally or for future work not yet evaluated). The recommended steps are:

- Further refine the draft worksheets, perhaps using previous project risk evaluations for comparison.
- Use the worksheets for evaluation of current or future projects to identify the benefits likely from this analysis.
- Assuming that the benefits identified are shown to be significant (in terms of their effect on BCRs), incorporate the worksheets (with any modifications identified) into the PEM procedures.

Future research was identified in the following areas:

- Further work into the elasticities of closure is needed. In many cases, not all of the traffic will delay or divert. The ideal approach would be to take some traffic count data on alternative routes during closure events and compare it with "normal" flows.
- The effect of closures on businesses needs further investigation. A number of reviewed studies made various assumptions on this, but a more direct examination, perhaps by means of willingness-to-pay surveys, may be necessary.
- The closure costs associated with both crashes and road works have not been investigated fully here in New Zealand. Further work is needed to quantify these effects and incorporate them in project evaluations.

Some methods for establishing failure rates of various hazards are provided for guidance. The link reliabilities of various simple networks have also been calculated.

## Abstract

This report develops project evaluation procedures to incorporate risk assessment of road link reliabilities. The current Transfund evaluation procedures and recent work in this area are reviewed and suggested directions discussed. Simple link reliability theory is then developed, as well as typical examples of how this theory could be applied. The application of this theory within a project evaluation context is also considered.

The study found that Transfund's *Project Evaluation Manual* (PEM) does not currently provide many analysis tools relating to risk and reliability. Although qualitative assessment of the hazards facing the existing road network is often done at a strategic level, quantitative evaluation of projects designed to improve the reliability of the existing road network could be provided in the PEM. Link reliability should be considered when the project is located on or affects the reliability of a strategic link, if there are two or fewer alternative routes and the project costs or benefits exceed a specified minimal level.

Draft procedures for incorporating the effects of link reliability into project evaluation are provided and it is suggested that they be trialled on relevant current or future projects. Areas requiring further research are identified and some methods for establishing failure rates of various hazards are also provided for guidance.

# 1. Introduction

This research set out to develop project evaluation procedures to incorporate risk assessment of road link reliabilities. It was envisaged that the procedures could be used for projects where new links were being created or where existing links were being upgraded.

Transfund New Zealand required an economic evaluation of the benefits and costs of all proposed roading projects, using its *Project Evaluation Manual* (PEM), Transfund (1999). The assumption generally made when a project was being evaluated was that the existing network would continue to perform as it stood, with "instantaneous" replacement of any damaged road or bridge section and no closures. This did not consider the economic consequences of delays in reinstating these links, or the relative importance of those links with few (or no) suitable alternative routes.

There have been a number of research initiatives in New Zealand to examine the risk of link closure or degradation inherent in our existing road network. Montgomery Watson (1998) reviewed the likelihood of severance, and the economic consequences of such severance. Dalziell *et al* (1999) used the Desert Road as a case study for developing risk assessment methods for road closure. Beca Carter Hollings & Ferner (BCHF) (1998) reviewed the state of knowledge for risk mitigation in New Zealand, albeit on a more general scale.

All of these projects were either derived specific risk likelihoods/frequencies of various closure events or specific costs of such events. There was still a need for the development of procedures to be incorporated into the PEM. Having identified the various risks and costs, and with a number of potential mitigation projects available, a means of calculating the Benefit/Cost Ratio (BCR) for these projects was required.

## 1.1 Objectives

The main objectives of this research were:

- To review the existing PEM procedures for deficiencies and identify areas where additional procedures may be useful.

  The recent research mentioned above and other relevant work would be reviewed to determine how it could help to remedy these deficiencies. Some recent strategic route studies would also be reviewed to determine what risk assessment procedures had been used in recent practice.

- To develop calculations for the effect of link reliability.

  Basic link-reliability theory would be derived for roading project evaluations. From this, general procedures for use in PEM project evaluations would be produced. Some example scenarios based on typical projects in New Zealand would be developed for testing to demonstrate the resulting procedures.

The outcomes from this study would:

- Provide procedures for strategic risk assessment to be incorporated into the PEM.
- Allow more accurate quantification of the BCR over a roading project's lifetime, particularly for projects of strategic importance.

## 1.2 Report Outline

Section 2 of this report reviews the current Transfund evaluation procedures and recent work in this area. A discussion suggests directions.

Section 3 develops simple link reliability theory based on the previous literature, and looks at some typical examples of how this theory can be applied. The application within a project evaluation context is also outlined.

Conclusions from this report are summarised in Section 4, followed by a list of references and appendices.

## 1.3 Reliability, Failure, Risk and Uncertainty

Before proceeding further, a few definitions and clarifications are needed. When we talk about "reliability", "risk" and the like, they often mean different things to different people.

In a traditional engineering context, "risk" is a combined assessment of the *likelihood* and *consequences* of a given event. Although the two individual components can usually be quantified, the combination of the two is largely a subjective assessment. Different people may assign a different relative risk to the same event. This is not helped by the effect of *context* on risk assessment, e.g. is it a risk for you personally or someone else.

For the purposes of this research, "risk" is generally taken to mean "the likelihood of a hazard resulting in subsequent route failure". This may also be referred to as the "failure rate". This usually has to be weighted by some measure of "exposure", i.e. (usually) the greater the exposure, the greater the chance of failure. In typical engineering applications, the expected number of failures is usually determined as:

$$\text{Number of Failures} = f\,(\text{Exposure}) \times \text{Likelihood} \qquad (1)$$

"Failures" may also be known as "hazard events". Technically though, it is the hazard event (e.g. a storm) that subsequently causes the failure (e.g. road closed due to slips).

Exposure may be in terms of traffic exposure (for the risk of crashes) or time exposure (for the risk of earthquakes). The function of exposure may be a simple linear one (i.e. double the exposure, double the failures) or something more complicated such as negative exponential functions.

Conversely, reliability is taken to mean the likelihood of the route remaining open. Given a known probability of failure, f, between 0 and 1, then the equivalent reliability, $r = (1-f)$.

Risk is not the same as uncertainty. Risk occurs when the likelihood of an event is<1. In other words, unless an event is 100% likely to occur, there is only a risk that it may occur. Uncertainty is when the level of likelihood or risk is not exactly known; e.g. it may range between, say, 0.02 – 0.05.

In most practical cases involving risk, there is also an element of uncertainty associated with the figures used. This is touched upon in some of the work later, but generally is not considered in this research. Currently, Transfund usually request sensitivity analyses of key parameters, such as traffic volumes, cost estimates or crash reductions. The combined effect

of these uncertainties however is not asked for, partly because of the calculation difficulties. Transfund is considering how to further incorporate uncertainties of values into their project evaluation procedures, via their corresponding evaluation software. The result may be a range of benefit/cost ratios and a most likely value as well. If link reliability is also taken into consideration by project evaluation in the future, then the values used could also be subject to the same uncertainty criteria.

Note also that this uncertainty is also different to the "severity uncertainty" that may be applicable for many hazards. For example, a range of different earthquake intensities may produce different effects on various road links. In this case, the various scenarios need to be combined to determine the expected effects resulting from such a hazard. This is looked at in Section 3.

The most recent revision of the PEM (1999) contains an addendum on Risk Analysis Guidelines. This is however focused on project risk during the formulation, evaluation and implementation of a roading project. These risks may include unforeseen increases in construction cost, incorrect traffic data affecting project viability and Resource Management problems delaying the project. Although the addendum is designed as a tool to guide Transfund and analysts on the potential scale of these risks, it does not seek to affect the actual BCR. By contrast, this report is concerned with the expected risks on the adjacent road network during the lifetime of the completed project, and will attempt to quantify the effect of these.

# 2. Literature Review

In recent times, increased interest in all aspects of roading risk assessment has seen a number of studies carried out in New Zealand. This is slowly being reflected in the PEM procedures, as they strive to include all relevant inputs of project evaluation. This section evaluates both the PEM and other relevant reviews.

## 2.1 Existing PEM Procedures

The latest edition of the PEM (Transfund 1999) contains a number of relevant sections that have implications on risk assessment or link reliability. As discussed in Section 1.3 above, there is also now an addendum on risk analysis guidelines, which will not be examined here further.

### 2.1.1 Basic Concepts (PEM Section 2)

The PEM section 2.12 deals with choosing the scope of the analysis. Two statements are relevant to this study:

> All realistic project options shall be evaluated to determine the optimum economic solution.
>
> Where the benefits of one project are partly dependent on completion of another project, then the projects are interdependent. Interdependent projects shall be evaluated both as a single combined project and as separate projects and the results of both analyses shall be reported.

This is particularly relevant to situations where a project does not address the "weakest link" of a route, but future projects may. For example, a project may reduce the likelihood of flooding (and subsequent closure) on a section of road, but another section may still be more likely to be flooded. Until the latter section is also upgraded, the full benefits of reduced closures may not be realised.

The PEM section 2.19 deals with uncertainty and risk, both in terms of:

- uncertainty about the size or extent of inputs to an analysis; and
- uncertainty about the timing and scale of unpredictable events

As discussed previously, the former category is not really of interest in this study. The PEM suggests sensitivity testing and probability distribution analysis (or risk analysis) should be applied in both of these cases, but no guidance is given here.

### 2.1.2 Specific Procedures (PEM Section 3)

The PEM section 3.4.10 introduces the concept of benefits arising from National Strategic Factors (NSFs) as a potential benefit (they are explained in more detail in PEM Appendix A9). NSFs are defined as "national benefits that are valued by road users or communities, but are not included elsewhere in the procedures". They may be incorporated as benefits in project evaluation where they:

- will have a material impact on a project's ranking,
- comprise national economic benefits,
- have not already been counted in the core analysis, and
- would likely be valued in a "normal" market.

One of the two categories of NSFs identified so far is that of "providing for security of access on busy inter-regional routes". Like this research, this factor attempts to identify

benefits associated with link reliability. However NSFs are considered similar to other intangible factors and are to be valued in the same way. This is a somewhat different approach to identifying tangible benefits associated with link reliability, which will be looked at later.

The PEM section 3.4.11 deals with strategic planning and highlights the need for project selection to be underpinned by robust strategic planning at regional, local and corridor levels. Although it considers such information as "integral to the assessment of the values ascribed to NSFs", it does not ask for anything more than descriptive details.

The PEM section 3.4.13 touches on unplanned disruption costs. It states that:

> Where there is a quantifiable risk that unexpected events may cause disruption to traffic flow, damage to vehicles or injury to road users, then the cost of these effects shall be included in the analysis. Where a project serves to reduce or eliminate the risk of such effects, then this will be a benefit attributable to the project.

The PEM states that either expected values or probability distributions of costs should be used, with reference to a later section (PEM Section 3.9) for guidance.

The PEM section 3.9 deals with projects involving risk. For all projects exceeding $10 million in capital value, a detailed risk analysis is expected, as it is of any project where the principal objective is the reduction or elimination of an identifiable risk. Other projects that involve some "significant" element of risk should also provide costs in terms of expected values (from an analysis of probabilities), although it is not defined what is considered significant. It is indicated that such risk analysis procedures should not apply to "minor risks such as occasional small slips". However, it would seem that this should be dependent on the expected costs of these risks, (especially where there are high traffic volumes and/or no alternative routes) rather than the nature or size of the hazard.

A general procedure for evaluating risk by analysis of probabilities and expected values is given, which is repeated below:

a) Identify the uncertain elements in the project and the chain of consequences for any unpredictable events.

b) Determine the costs to the project and the benefits or disbenefits to road users for each possible outcome.

c) Identify an annual probability of occurrence and the period of years over which this probability applies, for each uncertain element.

d) Compute the expected values of costs and benefits for the uncertain elements in each year as the product of the costs and the annual probability of occurrence. Include these in the project cost and benefit streams when carrying out the discounted cash flow calculations.

A worked example, based on the replacement of a bridge, is given. This assumes that a bridge will be replaced in five years if a 1-in-200-year earthquake does not destroy it before then. The example introduces simple success/failure binomial probabilities to calculate the likelihood of bridge survival. It also considers some of the likely disruption costs (such as temporary Bailey bridging) if the bridge was destroyed early. No explanation is given of the derivation of delay costs, although they could provide useful examples in their own right. Finally, calculation of expected values is shown by combining the possible outcomes.

The example does not explicitly consider the effects of link reliability (although the road user disruption costs may account for this). It also doesn't identify a project that aims to improve link reliability, although the example could be one of a number of options for when to replace the bridge (e.g. a "later replacement" option may have a greater expected value of costs). Such considerations could be added to the example to enhance the overall understanding of these concepts.

### 2.1.3 Simplified/Full Procedures (PEM Sections 4/5)

The PEM Simplified Procedure No. 2 (Structural Bridge Renewals) contains a Worksheet 4 that assesses Heavy Commercial Vehicle (HCV) user costs when there is an alternative route. In particular it considers where there are weight restrictions on routes, which may force HCV users to either make more frequent trips with lighter loads or use the alternative (unrestricted weight) route. The analysis is a simple one in that it only considers one possible alternative route in parallel with the route being analysed. Another sheet, Worksheet 5, is also available for situations where there is no alternative route.

Worksheet 2(a) of the Full Procedures (Description of the Project Options and Strategic Issues) asks for the "upstream and downstream impacts" to be described. This is considered to be "impacts that the project will have on the corridor or network, including future projects that are likely to be delayed or promoted by proceeding with this project." This would seem to include projects that have an effect on the reliability of a network and subsequently affect the relative merits of other projects. However, it merely asks for descriptive information, which may not be given as much weight by Transfund as a tangible benefit or cost.

### 2.1.4 Isolation (PEM Appendix A8.12)

One of the intangible effects mentioned in the PEM is that of isolation, due to either:

- unreliable roads; or
- living in remote areas threatened with isolation.

This particularly addresses concerns where roads and bridges are destroyed removing the only practical link out of an area. The PEM states that "where projects reduce isolation or the threat of isolation, the benefits shall be quantified, where possible." For intangible effects of this kind, non-market valuation techniques or ranking procedures are suggested and an earlier part of the section gives guidance on these. It also states that the isolation (or threat of) should be reported in descriptive terms, e.g. number of residents affected, availability of alternative routes, frequency/duration of closures, even visitor/tourist potential of the area.

### 2.1.5 National Strategic Factors (PEM Appendix A9)

The previously mentioned NSFs are outlined in detail in this appendix of the PEM. It makes the very good point that "roading projects, particularly large ones, are sometimes inappropriately described as 'strategic' if they cannot be justified by valuing the tangible (road user) and intangible effects".

In valuing NSFs, a comparison is made with the 'normal' market, i.e. would road users or communities be willing to pay for NSFs such as security of access, if they could. A common paradigm given is the use of insurance; people are able to insure their homes

against earthquake, for example, and may be willing to do the same for the routes that they rely on.

Security of access is considered important when there are few (or no) reasonable alternatives to a particular route. This NSF seeks to identify benefits in "providing a greater assurance to road users and communities that they will be able to depend on a particular route". Some of these benefits may already be quantified via travel time costs, but there may still be an additional intangible not accounted for. Care, however, needs to be taken to avoid double counting.

An example of how this NSF may apply to a project that reduces the likelihood and severity of a slip is given in sample PEM Worksheet 9.1 (section 5). This compares the project travel time savings with surveyed drivers' willingness to pay for the reduced obstruction and gives the difference as an NSF.

This NSF is an attempt to provide some measure for link reliability into the existing project evaluation procedures. There still appears to be scope for more tangible benefits to be determined and included (using techniques outlined later) before resorting to NSFs.

## 2.2 Other Relevant Studies

Montgomery Watson (1999) developed a methodology for determining the relative importance and vulnerability of links in New Zealand's "strategic" roading network. From this basic desktop analysis, four key roading links were selected for more rigorous examination, including consideration of potential improvements.

The initial ranking system is essentially an empirical method, with no assessment of tangible values. Arguably, it has more in common with the procedures for assessing NSFs. However, the detailed examination stage derives actual costs for both users and businesses. In this respect, the initial procedures could be useful for identifying when to use link reliability procedures.

The initial stage involved the following steps:

a) Establishing the network.
b) Defining strategic links and valuing their "strategicness".
c) Assessing vulnerability of each link.
d) Assessing impact of event for each link.

The ranking system measured three parameters:

- level of each link's strategicness,
- risk and length of time that link would be disrupted, and
- impact of severance.

The three were multiplied together to get a final score, then each link was ranked.

Strategicness was determined by four key factors:

- *Contribution to commerce (based on HCV volumes)*

  Links were graded 0 to 9 depending on the heavy traffic volume. An extra point was given for a link that is the only route to a transportation node (e.g. port) or major

commercial enterprise.

- *Provision of mobility to the community (based on car/LCV volumes)*

  Links with the highest traffic (no HCV) were given 10 and others according to the traffic volume.

- *Life-line (or heath and welfare) values (based on access to hospitals)*

  Small remote communities qualify as vulnerable if the population is over 500 and there is a single lifeline road connecting the hospital or alternative routes that are too long to be useful in an emergency. There also has to be no other viable access to hospitals e.g. train (unless likely to be severed as well), although small airfields could be considered. Links were also graded by size and seasonality of population.

- *Contribution to international tourism (based on tourist bus numbers)*

  Tourism importance is for routes that either access destinations or are scenic in their own right.

The factors were then scored from 1-10 and calibrated by a review group. Each factor was weighted in the final ranking, with commerce and mobility given the most emphasis.

Risk was weighted according to a combination of the return period for the event and the impact duration:

$$\text{Risk factor} = 100 \times [\text{No. Days of Disruption}] / [\text{Ave. Return Period (yrs)}] \quad (1)$$

For example, an event with a return period of 15 years and a likely disruption time of 3 days had a risk factor of 20 assigned to it.

The impact of the hazard on the network was also scaled between 0-10, depending on the typical delays encountered on alternative routes.

Montgomery Watson (1998) developed the above model further to prioritise at-risk links of state highways. The previous "simplified procedure" was used to identify risks that state highways are vulnerable to. For each strategic link, an overall ranking was determined, in terms of importance, risk of closure and impact of severance.

Each link could then be examined in more detail using "full procedures" that calculated the probabilities of hazards occurring and expected annualised closure times. A number of theoretical methods were presented for establishing typical failure rates for hazards such as snow, slope instability, and structural failure (see Appendix A.1 of this report). This enabled the impact of a link closure to be assessed in terms of disbenefits and costs.

Additional disbenefits associated with road user costs are:

- Additional vehicle operating costs due to travel via a longer or rougher alternative route.
- Additional travel time costs due to delays and longer/slower alternative routes
- Increased accident exposure on alternative route

Additional disbenefits associated with link failure are:

- Loss of revenue for transport firms or businesses on either side of the closure

- Loss of life due to structure failure
- Loss of life due to severance of health and welfare services

The longer the delay the more likely these disbenefits will increase.

Any improvement options available that could reduce the costs associated with these closures were evaluated for consideration of further work. A spreadsheet tool was developed to help with preliminary BCR calculations.

Savage *et al* (1998) set out a basic framework for lifeline organisations to assess the economic costs and benefits of mitigation works. They suggest that in order to rank projects and ultimately make decisions on the most necessary investments a sequential decision-making process and cost/benefit spreadsheet needs to be used.

They note that different lifeline organisations will have different interests based on their stakeholders, and this will influence the scope of their framework but not the underlying structure of the decision making process and spreadsheet. For example, privately owned organisations will place more emphasis on financial appraisal of links, and publicly owned organisations will have a more holistic approach considering not only the costs that directly affect them but the wider social cost and benefits.

The decision making process should include questions that concern the objectives, constraints, alternatives to investments, identified costs and benefits, and the valuations of costs and benefits. Social costs should be valued where possible in terms of tangibles, such as the cost of trucking in alternative supplies. This information can then be used to find out which projects have the highest benefit/cost ratios. As a last step, intangible factors can be considered that have not been included in the quantifiable decision making process.

Two types of spreadsheets are presented as examples. Both list costs/benefits and value them, but they differ in how they adjust cost and benefits to take into account the probability of a hazardous event occurring. The "simple probability" spreadsheet considers a single event. This can be calculated in one of two ways, by the expected value (cost/benefits multiplied by the probability of event), or by the conditional probability (costs/benefits if an event happened in a particular year). The "hazard curve" spreadsheet allows for all possible events and provides scope for more than one project to be assessed. It also shows the relationship between the probability of each possible event, and the expected net cost can be compared on various levels considering the various alternative projects. The choice of the two spreadsheets depends on the accuracy required and the available information.

The authors state that this approach is useful when looking at simple problems. However, if lifelines are interdependent, or the nature of the potential events is complex, a method such as the Monte Carlo approach (i.e. repeated random trials of variables to determine the long-term likelihood) may be worthwhile using.

Butcher (1984) looked at how risk analysis could be applied to improving SH73 between Canterbury and the West Coast. He also discusses the use of 'probabilistic' cost/benefit analysis (CBA) i.e. a range of BCRs rather than 'deterministic' CBA as at present.

Probabilistic CBA is of most benefit where there is uncertainty as it prepares decision-makers for the uncertainty. By contrast, existing sensitivity tests generally only inform what could happen as a result of a slightly different input. They do not however describe how likely that outcome is. Usually for determining CBA, the most likely value is used for calculation. This however does not usually equal the "expected value" (except where all inputs have a uniform distribution of values).

Butcher also discussed at length some of the various implications of closure. This is considered further in Section 3.3. The impacts depend largely on how much the route is seen as a "lifeline". Assessing whether a route/service is a lifeline depends on the potential loss imposed. This depends on:

- redundancy of supply (i.e. alternatives),
- possible speed of repair,
- user values.

Nicholson (1996) notes that New Zealand is particularly vulnerable to impacts on its transportation network. As well as having a relatively high proportion (33%) of Gross National Product (GNP) associated with transport, the country is susceptible to a number of natural hazards, including earthquakes, volcanic eruptions, and storms. The geology and topography of the country make the transportation system prone to bridge failures, landslides and the like.

Nicholson suggests allowing for "degradation" in our transport models, causing reductions in traffic capacity and increasing the variability of travel times and/or distances.

He also points out that unreliability in a transport system can also arise without system degradation, in a congested network for example. Although all links are still available to travellers, travel times can vary widely because of even small variations in travel demand. Although this is partly considered in existing projects by considering the changes in delay and mean travel times, it has been suggested that travellers are more sensitive to the potential variation in these values. For example, travellers may prefer a route with a mean travel time of 30 minutes and a 95$^{th}$ percentile time of 35 minutes over a route with a mean of 25 mins and 95$^{th}$ percentile of 50 mins.

Nicholson & Du (1997) develop such a system for degradable transportation links, using an integrated equilibrium model with elastic travel demand. They note that when routes are closed or partly closed, the generalised cost of travel will change. There are a number of underlying changes to travel behaviour that can occur:

- trip-making may increase or decrease (trip generation change)
- existing trips may be made from/to new origins/destinations, or at a different time (spatial or temporal trip distribution change)
- existing trips may be made using different transport modes (modal split change)
- existing trips may be made via different routes (trip assignment change)

These changes cover the four main steps in a "traditional" transportation network model, so it can be seen that link reliability can affect all aspects of travel.

To determine benefits in proposed projects, Nicholson & Du establish the "system surplus" (based on the difference between supply and demand costs) in their equilibrium model.

Unlike network reliability, which is merely a measure of the connectivity of the system, system surplus measures the extent of the socio-economic impact of the system degradation.

Lunn (1996) sets out a methodology for planning to minimise the risk of hazards for a "lifeline" asset owner. The basic procedure is:

(i) examine past research
(ii) identify and analyse hazards
(iii) compare effects of each hazard on lifeline
(iv) describe vulnerability of lifeline
(v) compare lead times for underlying repairs (between identification and possible repairs)
(vi) describe interdependence of each lifeline (design and approval etc.)
(vii) identify options for preventing/mitigating the effects of hazards

He also summarises the requirements to assess for each hazard:

- intensity (i.e. how big/fast/powerful)
- frequency vs likelihood
- extent of network affected
- disruption/damage to network links

Augusti & Ciampoli (1998) examined procedures for the best allocation of resources that would help prevent disruption of lifeline systems during an emergency (disaster). If the vulnerabilities in the system were known then it was possible to derive the reliability of the network as a whole. Finding the best protected elements of the system meant saving on economic resources. The focus of the paper was on bridges.

By changing the weightings used in the optimisation, a solution could be obtained that was best for either network reliability, traffic capacity, delays, or some other objective (or combination of).

For road controlling authorities, a network optimisation tool such as that described can help to assign limited resources to improving the most critical links first. Detailed examination of such models (especially when applied to a complex network of many links) is beyond the scope of this study.

Dalziell *et al* (1999) used stochastic modelling to determine the probabilities and likely durations of closure of the Desert Road due to natural hazards, with an example for snow/ice closure given. For each event, stochastic relationships were established between the magnitude of the event and the duration of the road closure that might result. The total risk of closure was determined using Monte Carlo simulation for each risk component.

The authors then looked at the application of such road closure information to road network evaluation. A simple traffic network model was developed for the Central North Island to illustrate the effects on travel costs of closing the Desert Road and surrounding routes. Decision analysis software was also developed to optimise closure risks over a network.

Works Consultancy Services (1990) examined the vulnerability of the State Highway network assets to earthquakes and volcanic eruptions. They calculated expected damage costs by assigning "damage ratios" to structures given a particular hazard event. The damage ratio was defined as:

$$DR = [\text{Cost of repair}] / [\text{Replacement cost}] \quad (2)$$

For a given earthquake intensity $I_j$, a structure having a value of $\$V_r$ will have a damage ratio of $DR_{jr}$ and can expect to suffer $\$(DR_{jr} \times V_r)$ worth of damage. To simplify matters, structures of similar type and age can be assigned the same damage ratios for given events. If the earthquake $I_j$ has an annual probability of occurrence $P_j$, then the expected annual "exposure" cost of damages to all assets is:

$$\text{Total } \$ = \Sigma_r \Sigma_j DR_{jr} \times V_r \times P_j \quad (3)$$

(where $\Sigma_x$ is the sum over all values of $x$)

Worley (1998) reviewed the traffic and economic impacts of closure in the Manawatu Gorge and assessed the viability of improvements to alternative routes. The physical costs and user costs of closures were compared against the benefits attributed to upgrading either of the adjacent Saddle Road or Pahiatua Track Road alternatives.

This was based on comparing the costs for the "normal" traffic operation with the costs for the "emergency" situation (i.e. the gorge closure). Using historical data of closures, the existing net cost of operation through the gorge over 25 years could be determined. Similarly, the net cost of improved operation could be established, i.e. from fewer closures or improved service during closures. The difference could be combined with a cut-off BCR to back-calculate the level of expenditure justified to improve the route.

This approach provides a feasible means of establishing BCRs for simple improvements to small networks. It is simplified by the fact that only one link (the dominant route) is examined in terms of reliability; all other links are assumed to be "fully" reliable (or at least, relative to the dominant link). For networks where a number of links are relatively susceptible, more complex reliability calculations may be required.

Beca Carter Hollings & Ferner (BCHF, 1999) assessed the likely economic and strategic effects of closure for State Highway 3 between Taranaki and Waikato. This section of road was subject to frequent closures due to slips, including a number of significant ones in the previous two years. There was a reported perception in Taranaki that this susceptibility to closure and the tortuous nature of the route in general made the region appear remote and cut off from the north of the North Island. The economic impact of this may not be fully recognised by Transfund project evaluation, although one has to remember that any transfer of benefits between regions is not considered.

BCHF (1999) refers to other research that has found that travellers can value a reduction in uncertainty of travel time as much as (if not more than) the equivalent journey travel time savings. Similarly, travel time costs for closures may be underestimated by using Transfund travel time values, which are based on willingness to pay for travel time savings, rather than willingness to accept travel time losses. Further investigation of these considerations is beyond the scope of this study. However, any other findings may be relevant to the potential use of travel time savings in link reliability analysis.

Other general texts on risk assessment and reliability engineering were also reviewed, such as Henley (1981), Frankel (1988) and Modarres (1993). These helped to form the basis of the theory in Section 3.

## 2.3 Discussion

The PEM does not currently provide many evaluation tools relating to risk and reliability. In summary:

a) Security of road access is only explicitly mentioned in the context of intangible NSFs and "isolation" effects, and not using tangible assessment means.

b) It is not defined what is considered a "significant" risk to warrant the use of risk analysis (other than being mandatory for projects with >$10m capital cost).

c) No guidance is given on derivation of delay/detouring costs.

d) There is no specific example of link reliability being considered as part of the risk analysis section.

e) Only the simplified procedures for Structural Bridge Renewals contain any reference to the availability of alternative routes.

f) The "impacts that a project will have on the corridor or network" are only explicitly asked for in descriptive detail in the Full Procedures worksheets.

Arguably, this is because most projects do not need to consider risk analysis and link reliability in their evaluation, and it can be quite a specialised topic. However, some of the other publications reviewed demonstrate good examples of material that could be added or at least provide a base for developing such material.

An informal review of some project evaluations by the author suggests that analysts have individually developed their own methods for assessing reliability considerations as required. This has the effect of producing inconsistency in presentation and interpretation. For example, evaluation of two projects affected by similar hazards may be based on quite different assumptions and derived calculations. Although it is difficult to cater for every conceivable situation, it appears that some generic worksheets for risk analysis in the PEM could help to provide some consistency.

There appear to be two distinct phases in assessing network reliability:

(i) A partly qualitative assessment of the hazards facing the existing road network. This is usually to identify which links appear to be the most critical, i.e. vulnerable to potential damage or closure. Montgomery Watson (1999) and Lunn (1996) both discuss such procedures, which could be either a descriptive exercise or use empirical methods to "quantify" the risk. Because this exercise is largely at a strategic rather a project level, there is little potential for incorporating it into the PEM. However, it is an important step in identifying suitable projects, as it is likely to highlight those with the most promise for subsequent high BCRs.

(ii) A quantitative evaluation of projects designed to improve the reliability of the existing road network. Worley (1998) provides a good example of a simple analysis of road links, while Augusti & Ciampoli (1998) demonstrate a network-wide optimisation of resources for many projects. It is in this area that further detail and refinements could be provided in the PEM, for individual projects at least.

The literature also highlights the two main decisions to be made concerning the improvement of a link. Either a link can to have its components "strengthened" (where "components" may include its back-up routes) or, alternatively, new links can be created. In some areas, there is a lot of redundancy in the road network, meaning that the former approach is more useful. In other areas where there are fewer links, it may be useful to improve the supply of links in that network.

An approach that only considers the potential severance effects on major strategic routes makes sense, given that they carry the bulk of the country's traffic necessary for our commercial, welfare, and recreational needs. Indeed, one of the criteria for when to consider link reliability effects should be to use it only in relation to strategic routes. However, it is important to remember that when analysing a particular strategic link it may be dependent on relatively minor routes in times of closure or other restriction. Worley (1998) demonstrated that well with the two alternative routes to the Manawatu Gorge highway. Any sealed road within reasonable connecting distance to the original route should be considered as a potential alternative route; in some cases nearby unsealed sections may also be appropriate.

The effect of link reliability could also extend to crash costs. At present, project evaluation assumes standard costs for different crash severities (i.e. fatal, serious, minor, non-injury). There are slight adjustments incorporated to account for different speed environments, vehicle types involved and crash types; but the resulting values are still of the same order of magnitude.

It could be argued however that this does accurately reflect costs when a crash occurs on a link with few or no alternative routes and the resulting disruption blocks the road. There are considerable time delays for following vehicles while they wait for the wreckage to be cleared. This is particularly so during peak traffic periods when, accordingly to the law of exposure, the crash risk is also the highest.

A typical example would be on SH1 north of Wellington between Plimmerton and Paekakariki, where delays of 1-2 hours are common following crashes. Over 20,000 veh per day travel this (largely two-lane) route, with peak hour flows of 2000 veh/hr. Within this section, there are no alternative routes, with the winding Paekakariki Hill Rd route connecting at each end. If 2000 vehicles are stopped for an hour then, using the current PEM travel time and congestion values, about $40,000 of additional vehicle travel time is incurred. Between 1993-97 over 80 injury crashes occurred along this section of highway, of which many can be expected to have caused lengthy delays. Assuming only 10 hours of delays per year due to crashes, then around $4 million of travel time costs could be incurred over a 25-year analysis period. This simple analysis does not consider costs associated with other closures such as slips.

If an alternative route is proposed for construction (such as Transmission Gully), then one of the potential benefits is to reduce these crash delay costs on the existing route. There is still likely to be some delay time, particularly until the extent of the blockage is realised by travellers, and there may be additional diversion time to reach the alternative route. However, for some projects, the resulting crash delay benefits may be significant and have a useful impact on their BCR.

Negating this may be the fact that the construction of the project itself can cause considerable delay to travellers. If there is no alternative route then the opportunities for motorists to minimise this problem may be few. Therefore, the benefits provided by improving link reliability may be reduced because of the reduction in link reliability during construction.

Unlike the other hazards considered, road works can generally be specifically planned for in advance. Some work has been done in this area locally by Tate & Major (1993) and Farrelly & Koorey (1997). However, it is still an area requiring more attention at the project evaluation level, given the potential impacts on user costs. Some projects that meet the BCR cut-off criteria for benefits once constructed may suffer due to the disruptions caused during construction.

# 3. Link Reliability Theory

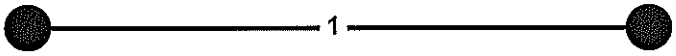
From the review of risk assessment literature, a number of aspects of basic link-reliability theory could be identified for further examination. From these, applications to PEM project evaluations are considered in this section.

## 3.1 Determining Failure Probabilities

Although this research is primarily aimed at how road networks affect link reliability and subsequently BCR evaluation; the literature review has highlighted a need to provide some basic information on assessing failure probabilities. Although each hazard has its own particular features concerning likelihood, there are some general concepts that will be dealt with here.

Consider a road route (or "link") between two locations (or "nodes"):

**Figure 3.1 Simple Road Link between Nodes**




There is a probability, $f_l$, that this route will be closed for some reason, i.e. the link will "fail". Conversely the link has a reliability, $r_l$, of staying open, i.e. $r_l = 1 - f_l$. If this is the only link between the two nodes then this is also the overall reliability, R, of the network.

In practice, most road links have a very small probability of failure, as potential hazards such as major slips and flooding are rare. However, over a 25-year analysis period, the likelihood of such failure events happening may be significant. For example, if the probability of a road being closed for any given half day is 0.005 (or 1 in 200), then you may expect road closures on the route totalling almost 100 half days (= 1200 hours) over that period. The national costs of these closures to the community (particularly to travellers and businesses) may be quite substantial. Therefore, it is important to establish an accurate estimate of these failure probabilities.

Montgomery Watson (1998) suggests a two-tiered approach to determining failure rates depending on the frequency. Where an event happens regularly (e.g. a number of times in a decade), it is probably most practical to use historical data (such as that maintained by network maintenance consultants) to establish typical closure patterns. Where an event is very rare (or may never have occurred in recorded history), then a theoretical "causative" algorithm should be determined to calculate the expected probability. For example, snow closures in a relatively temperate area could be established from the NZS4203 relationship for snow depth, given details about the snow zone and elevation of a particular road section (see Appendix A.1 for more details).

Dalziell *et al* (1999) make the point that not only does historical data have to be of "sufficient" quantity to be useful, it must also be based on the same conditions currently present or expected in the future. For example, the decisions behind closures in the past may be different to those made now, given the changing social and political environment. Improved technology may mean that closures can be minimised whilst, conversely,

legislation such as the 1992 *Health and Safety in Employment Act* can result in a more conservative approach to lifting closures.

One advantage in using theoretical (causative) methods that rely on environmental data (such as rainfall or earthquakes) is that there is likely to be a longer record of conditions than that of road closures.

To improve the predictive ability of available data, it may even be practical to combine both historical and theoretical data. McKerchar and Pearson (1989) demonstrate this approach when examining flood frequencies in New Zealand. If the historical and theoretical estimates ($E_h$ & $E_t$) are normally distributed, then a "pooled" estimate $E_p$ can be determined by:

$$E_p = s \times E_t + (1-s) \times E_h \quad (1)$$

and

$$\mathrm{var}(E_p) = s \times \mathrm{var}(E_t) \quad (2)$$

where the "shrinkage factor" $s$ is determined by a combination of the variances:

$$s = \mathrm{var}(E_h) / [\mathrm{var}(E_h) + \mathrm{var}(E_t)] \quad (3)$$

Where a hazard has a range of intensities, it is common to specify a return period associated with each intensity. This can be inverted to give the expected probability of such an event occurring in any given year. For example, a flood level with a return period of 50 years has a 1/50 or 0.02 chance of occurring in a year. If the costs associated with this event have been quantified then the expected annual cost can be determined by multiplying the cost by the probability.

When combining various intensities for an overall expected cost, it is important to remember that probabilities are usually given for an event of *at least* the stated intensity. Therefore, the probability of an event of greater intensity has to be subtracted from the next lower intensity, to avoid double counting.

For example, given the following determined information:

| Hazard Intensity | Return Period | Estimated Costs |
|---|---|---|
| 1 | 10 years | $2.2m |
| 2 | 50 years | $3.8m |
| 3 | 200 years | $5.6m |

the overall annual expected cost of this hazard is:

$$[(1/10-1/50) \times 2.2] + [(1/50-1/200) \times 3.8] + [(1/200) \times 5.6] = \$0.261\text{m}$$

Another consideration, particularly when historical data is available, is the effect of previous repair works. BCHF (1999) points out that remedial works following previous closures may actually improve the reliability of a route (or that of alternative backup routes).

Appendix A.1 gives some sample methods for establishing failure rates based on the literature review. Although they provide relatively simple means of assessing hazards, care should be taken in how they are used. Where appropriate a geotechnical, hydrological or structural engineer should be involved to review the calculations.

## 3.2 Networks in Series & Parallel

The key intention of this research is not to study links in isolation but, rather, look at networks of links that provide connection between any two given points. Where a particular hazard can affect a number of links, then its overall effect on the network needs to be assessed.

There are two basic types of network connection: series and parallel. Links in **series** require the traveller to traverse each link in succession, i.e.:

**Figure 3.2 Road Links in Series**

Each link has a separate reliability, $r_1$ and $r_2$ respectively and corresponding failure rates, $f_1$ and $f_2$. In this case, the overall reliability of this network, R, is obtained by multiplying the individual reliabilities together (assuming independence of links), i.e.:

$$R = S\{1,2\} = r_1 \times r_2 \tag{4}$$

For very small failure rates, the overall reliability can also be approximated by:

$$S\{1,2\} = 1 - (f_1 + f_2) \tag{5}$$

Additional links in series produce similar calculations, i.e.

$$S\{1,2,3,\ldots\} = r_1 \times r_2 \times r_3 \times \ldots \tag{6}$$

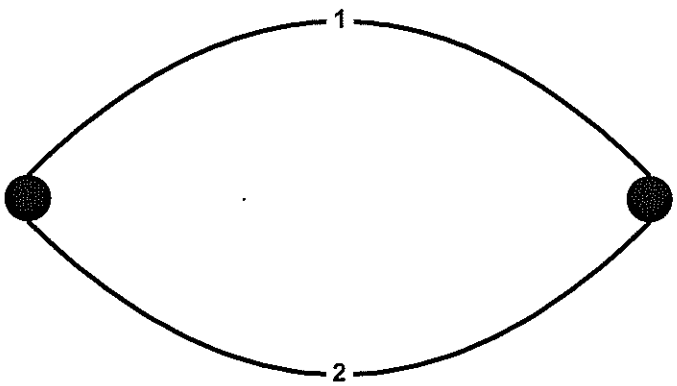
or

$$S\{1,2,3,\ldots\} = 1 - (f_1 + f_2 + f_3 + \ldots) \text{ (approximate)} \tag{7}$$

$$= (1-f_1) \times (1-f_2) \times (1-f_3) \times \ldots \text{ (exact)} \tag{8}$$

By contrast, links in **parallel** provide the traveller with a choice of links with which to reach their destination, i.e.:

**Figure 3.3 Road Links in Parallel**




In this case, the overall reliability is determined by combining the individual failure rates:

$$R = P\{1,2\} = 1 - (f_1 \times f_2) \tag{9}$$

This can also be expressed using reliabilities as:

$$P\{1,2\} = 1 - ((1-r_1) \times (1-r_2)) = r_1 + r_2 - (r_1 \times r_2) \quad (10)$$

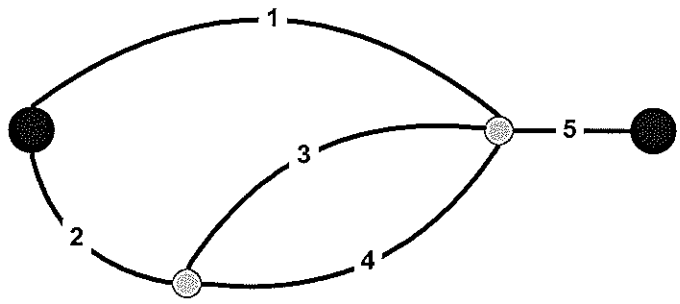
Again, a similar pattern applies to larger numbers of links in parallel, i.e.:

$$P\{1,2,3,\ldots\} = 1 - (f_1 \times f_2 \times f_3 \times \ldots) \quad (11)$$

### 3.2.1 More Complex Networks

In practice, there may be a number of alternate routes resulting in a more complex network of parallel and series links, e.g.:

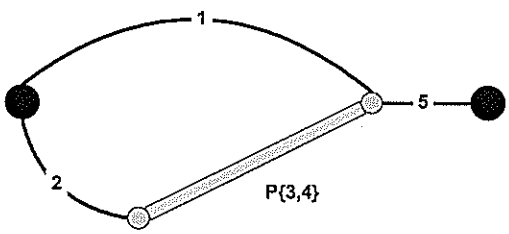
**Figure 3.4 More Complex Road Network Example**



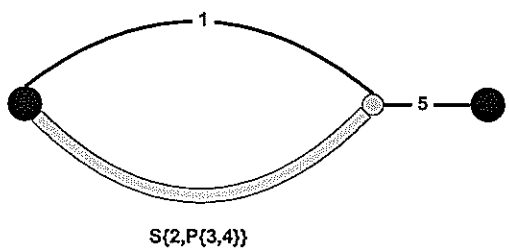

To resolve the overall reliability of this network, the links need to be combined one by one as simple pairs of either series or parallel links, i.e.:

**Figure 3.5 Resolution of Complex Road Network Example**

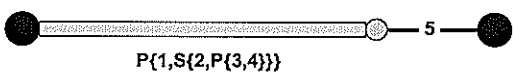
**Step 1:**



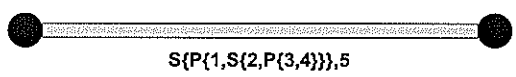

**Step 2:**




**Step 3:**




**Step 4:**

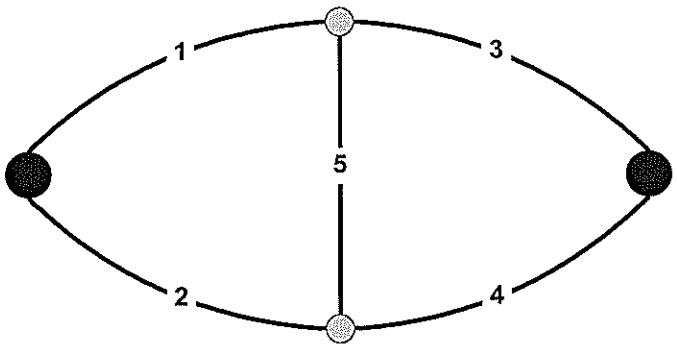



The resulting equation can then be used to calculate the overall reliability:

$$S\{P\{1,S\{2,P\{3,4\}\}\},5\} = (1-((1-r_1) \times (1-(r_2 \times (1-((1-r_3) \times (1-r_4)))))) \times r_5 \quad (12)$$

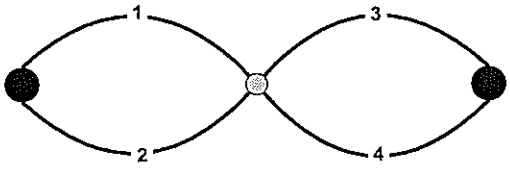
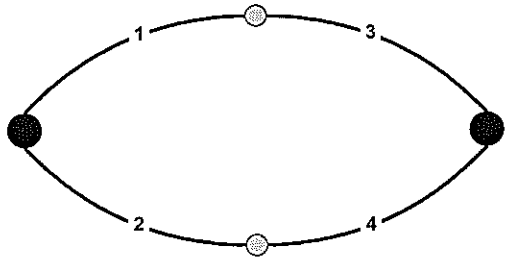
Routes that are more complex can also contain links that are neither in series nor in parallel, i.e.:

**Figure 3.6 Road Network with Non-Parallel/Series Link**




Unlike the above situations, link 5 cannot be easily reduced as part of a series or parallel set. In this case, the overall reliability has to be considered for the two separate cases where link 5 is either available or unavailable. Then combine these by weighting the two cases by the reliability of link 5.

**Figure 3.7 Resolution of Road Network with Non-Parallel/Series Link**

| Link 5 Available: ($prob^y = r_5$) | Link 5 Unavailable: ($prob^y = 1\text{-}r_5$) |
|---|---|
|   |   |
| $R = S\{P\{1,2\},P\{3,4\}\}$ <br> $= (1 - ((1\text{-}r_1) \times (1\text{-}r_2))) \times (1 - ((1\text{-}r_3) \times (1\text{-}r_4)))$ | $R = P\{S\{1,3\},S\{2,4\}\}$ <br> $= 1\text{-}( (1\text{-}(r_1 \times r_3)) \times (1\text{-}(r_2 \times r_4)))$ |

Therefore,

$$R = r_5 \times (1 - (1\text{-}r_1) \times (1\text{-}r_2)) \times (1 - (1\text{-}r_3) \times (1\text{-}r_4)) + (1\text{-}r_5) \times (1\text{-}(1\text{-}(r_1 \times r_3)) \times (1\text{-}(r_2 \times r_4))) \quad (13)$$

It can be seen that the resulting calculations can very quickly get quite complicated as the number of links increases. Fortunately, the relative effect on link reliability of changing individual reliabilities reduces quickly as the network grows. For example, in the two previous network examples, if the reliability of each link were 0.90 then the overall reliability would be 0.890 and 0.978 respectively. If we changed one of the link reliabilities to 0.95 (i.e. improved the link) the following overall changes would occur:

**Table 3.1 Effect on Overall Reliability of Changing One Link**

| Link to change r=0.90 to r=0.95 | Overall Reliability Figure 3.4 | Overall Reliability Figure 3.6 |
|---|---|---|
| none | 0.890 | 0.978 |
| 1 | 0.895 | 0.983 |
| 2 | 0.895 | 0.983 |
| 3 | 0.891 | 0.983 |
| 4 | 0.891 | 0.983 |
| 5 | 0.940 | 0.979 |

It can be seen that generally there is little change; only the most outer-lying link in Figure 3.4 (link 5) has an effect proportional to the change in its value. In this case, it is acting like a simple series network, which is considerably easier to analyse.

In reality, each link probably will have a different likelihood of closure, so the relative effects of changing each link may vary. However, at this level of network complexity the overall effects will still be relatively minimal. Therefore it is generally sufficient to only consider network reliability for links where there are ***two or fewer*** "alternative routes".

Appendix A.1 summarises a range of simple networks and their respective overall reliabilities. It should be noted that for some configurations, calculation using link *failure rates* instead would be simpler. This also has the advantage in that most hazard risk analysis is in terms of failure rather than reliability.

### 3.2.2 Independence of Links

The above calculations assumed independence of failure rates between individual links. In practice this is not always the case and must be carefully considered.

For any two given links with reliabilities $r_1$ and $r_2$ , independence is assumed when:

$$P(r_1 \mid r_2) = r_1$$

where $P(r_1 \mid r_2)$ is "the probability that link 1 is open *given* that link 2 is open". In other words, the availability or otherwise of link 2 has no bearing on the expected availability of link 1. The same equations can also be applied to probabilities of failure instead. To convert between conditional probabilities of failure and reliability:

$$P(r_1|r_2) = [r_1 - f_2 \times (1 - P(f_1|f_2))] / r_2 \qquad (14)$$

If two links are not independent of each other, then the basic reliability calculations have to be amended:

$$S\{1,2\} = r_1 \times P(r_2|r_1)$$
$$= r_2 \times P(r_1|r_2) \qquad (15)$$
$$P\{1,2\} = r_1 + r_2 - (r_1 \times P(r_2|r_1))$$
$$= r_1 + r_2 - (r_2 \times P(r_1|r_2)) \qquad (16)$$

Assuming independence when it is not the case:

- under-estimates system reliability when link components are in ***series***.
- over-estimates system reliability when link components are in ***parallel***.

As Butcher (1984) suggests, analysts must consider whether adjacent road links are truly independent of each other. For example, the chance of flooding one section of road may be related to flooding in another section.

It is likely that individual sections are not truly independent of each other because storm events may affect a number of sections. However, improvement of a section could reduce the probability of closure and/or length of closure.

Consider two alternative routes, A and B. If independent of each other then

$$P(\text{both routes closed}) = P(\text{A closed}) \times P(\text{B closed}) \tag{17}$$

If A & B are negatively correlated then

$$0 \leq P(\text{both}) \leq P(A) \times P(B)$$

e.g. westerly storm affects one route, easterly storm another route

If A & B are positively correlated then

$$P(A) \times P(B) \leq P(\text{both}) \leq \min\,[P(A), P(B)]$$

The latter situation is most likely the case for most roading hazards. Dalziell *et al* (1999), for example, found that the duration of closure of the Desert Road was reasonably correlated to the number of alternative routes also closed.

### 3.2.3 Cut-Sets and Tie-Sets

The calculation of some road network reliabilities can be quite cumbersome as seen above. An alternative method to establish the expected reliability is to use cut-sets and tie-sets.

A cut-set is a set of links in a network that would cause no through route to be available if they all failed. A minimal cut-set is the smallest set of links needed to guarantee such an interruption. In practice, there may be a number of minimal cut-sets that would cause this. For example, in Figure 3.4, the minimal cut-sets would be {5}, {1,2}, and {1,3,4}. If any of these sets of links were missing, then there would be no way to get completely through the network.

The probability of all links in a cut-set {A} failing, C{A}, is equal to the individual failure probabilities multiplied together (assuming independence), e.g.

$$C\{1,2\} = f_1 \times f_2 = (1-r_1) \times (1-r_2) \tag{18}$$

If $f_i \ll 1$ (say, < 0.3), then the overall reliability of the network is constrained by

$$R \geq 1 - (C\{5\} + C\{1,2\} + C\{1,3,4\}) \tag{19}$$

Tie-sets (or "path sets") are sets of links in the network that would guarantee a route through, with minimal tie-sets being the least number of links required to achieve this. For example, in Figure 3.4, the minimal tie-sets would be {1,5}, {2,3,5}, and {2,4,5}. If any of

these sets of links were all open, then there would be at least one way to get completely through the network.

The probability of all links in a tie-set {A} being open, T{A}, is equal to the individual reliability probabilities multiplied together (assuming independence), e.g.

$$T\{2,3,5\} = r_2 \times r_3 \times r_5 \tag{20}$$

If $r_i \ll 1$ (say, < 0.3), then, the overall reliability of the network is constrained by

$$R \leq T\{1,5\} + T\{2,3,5\} + T\{2,4,5\} \tag{21}$$

In practice, the failure rate is more likely to be much smaller than the corresponding reliability. Therefore, this bound may not be particularly useful. However the cut-set bound can still be useful on its own, given that $R \leq 1$ in all cases. The advantage of these constraints lies in being able to ignore dependence effects.

## 3.3 Effects of Route Closure or Degradation

When a highway link is closed, travellers have a number of options, with assumed costs involved:

- use alternative road (⇒ cost of detouring > cost of normal route when open)
- use alternative rail/air/sea (⇒ cost of transfer < cost of detour)
- not make the trip at all (⇒ cost of cancelling < cost of alternatives)
- wait until reopening (⇒ cost of deferring < cost of alternatives)

Dalziell *et al* (1999) identified the user benefit lost by travellers who cancel trips because of increased costs:

$$UB_{ij} = \tfrac{1}{2}(C_{ij} + C_{0ij}) \tag{22}$$

where

$UB_{ij}$ = user benefit of making one trip from *i* to *j*,

$C_{ij}$ = cost of travel from *i* to *j* normally,

$C_{0ij}$ = cost of travel from *i* to *j* when decision made to cancel

The cost can be established by combining the travel time, VOC, and accident costs of the proposed travel route. This assumes a uniform distribution of travellers who would cancel their trip given a cost somewhere between the two extremes. For this analysis method, an idea of origin-destination demands is also required which, for a given link contributing to a number of routes, may not be so easy to derive.

Link closure also affects non-travellers. Retailers may lose business or have to carry higher stock levels. Employees may not be able to work because of supply problems, etc. To date these costs have largely been ignored from analysis, although the introduction of "security of access" NSFs may provide a useful tool here, albeit intangible.

Montgomery Watson (1999) expressed similar concern about the need for research into business costs of closures. If trips are unable to be made on either the original route or any alternative route, there must be a mechanism for adding in costs. For their analysis, Montgomery Watson used travel-time costs over an 8-hour working day as a baseline. A 30% return on investment was considered a reasonable business expectation. This was

applied to the traffic volume that would not travel because of the closure, and halved to account for return journeys. Therefore:

$$\text{Lost business \$/day} = [\text{Cancelled Trips/day}] / 2 \times 30\% \times 8\text{hr} \times [\text{Travel time \$/hr/veh}] \quad (23)$$

Care needs to be taken to ensure that the lost business costs are not being recovered at another location through increased business there. Transfund's project evaluation procedures are concerned with national benefits & costs and not transfers of these between areas. For diverted trips, there is not likely to be a net loss of business, whereas a cancelled trip may eliminate some business transactions completely.

Closure of a route may cause trip suppression. Typical elasticities for this are unclear and further research is needed. For the purposes of this study, "elasticity" can be defined as:

$$\text{Elasticity} = (\%\text{Decrease in Traffic}) / (\%\text{Increase in Travel Costs}) \quad (24)$$

For example, if a closure causes travellers to take an alternative route that doubles their travel costs (100% increase), an elasticity of 0.20 will see a 20% reduction in trips made via the alternative route. This does not include existing trips already present on the alternative route.

Elasticity varies with duration of closure, cars versus commercial vehicles (often zero elasticity for the latter), and forecast of opening time. Therefore, different elasticities may be needed on different routes and for different hazards. It also tends to change over time.

Conversely, improvements in roads may see an increase in travel demand on a route from other than diverted traffic (i.e. induced traffic). BCHF (1999) suggests possible elasticities of between 0.5 and 2.0 for such improvements. This increased traffic needs to be accounted for in BCR calculations. Technically the extra traffic adds further road user costs per additional vehicle, yet there is an apparent benefit for the vehicles concerned. This benefit could be calculated accordingly using a demand elasticity method:

$$[\text{Ave \$ Saving per veh}] = [\text{\$ Benefits of Improvements}] / [\text{Total Vehs over 25 years}] \quad (25)$$

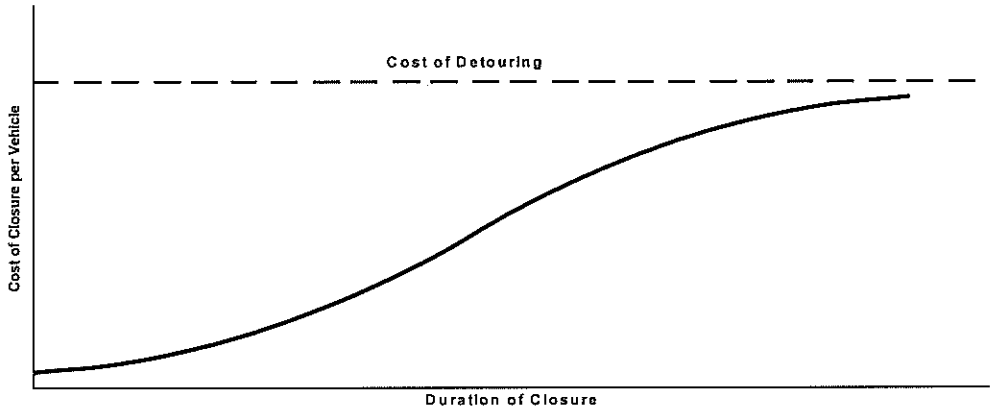
$$[\text{Increased Traffic \%}] = \text{Elasticity} \times [\text{Ave \$ Saving per veh}] / [\text{Trip Cost per veh}] \quad (26)$$

$$[\text{NPV of Induced Demand}] = \tfrac{1}{2} \times [\text{Increased Traffic}] \times [\text{Ave \$ Saving per veh}] \quad (27)$$

Both the costs/benefits and vehicle numbers have to be discounted to produce Net Present Values.

The alternative to detouring is to defer the trip until the original route is reopened. Although deferred time can usually be productively put to use on something else, there is still an "inconvenience" cost while waiting, which needs to be added to the actual travel time. These closure costs are likely to be non-linear over their duration. Figure 3.8 (from Butcher 1984) demonstrates this.

**Figure 3.8 Likely costs of Closure over Time**




Because of the non-linear relationship, an analysis using the average closure duration will not suffice. The expected cost from probabilities of all closure durations needs to be determined.

In theory, it may be possible to deliberately close a link and allow other links to carry the traffic. The maintenance savings may outweigh the costs to travellers. Opus (1998) outlines some calculations for justifying the retention of some bridge access when reviewing options for the replacement of two old bridge structures. Typical benefits of retention include:

- road user costs saved for detoured trips (i.e. longer alternative route),
- road user costs saved for diverted trips (i.e. trips to new destinations),
- economic cost of job losses, school transfers, etc,
- safety costs from requirements such as additional fire/police/medical services,
- road user costs saved for having an alternative route available for other roads.

The resulting total benefits can then be divided by the NPV for a basic bridge crossing to obtain a BCR for retention. This is not the same as a BCR for replacement of an existing facility however. As an aside, Opus noted that the current economic evaluation methodology heavily discounted future expenditure, favouring options that defer large costs (e.g. by extra maintenance) over immediate replacement options.

There may be a possible change in crash costs associated with trip changes. However, given the relatively short time of closure (usually) this may not be significant to warrant examination.

For some routes there are not just closure restrictions; there may also be height / length / weight restrictions. For example, a route may not be open to class I weights. A number of sections may need to be improved before it is. The full benefits of these projects therefore are dependent on the other projects occurring.

The above reliability calculations are based on road links being either available at full capacity or completely failed. As Nicholson (1996) pointed out, existing network models do not usually consider the case where a link may be only partly available (e.g. slips block one lane), which may result in additional delays. If a road has excess capacity, then this resulting reduction in capacity may not be critical. For example, given a two-lane rural road with a typical capacity of over 2000 veh/hr, a small slip blocking one lane may have minimal effect on, say, 400 veh/hr. Failure scenarios must therefore be selected that will

actually cause a noticeable impact on route performance. One also has to bear in mind that there may be safety issues associated with reduced capacity.

## 3.4 Application to Project Evaluation

From the literature review, it is evident that there are a number of likely hazards that can affect road networks. These include:

- flooding
- slips/landslides
- snowstorms
- avalanches
- structural collapse
- accidents
- earthquakes
- ice
- rock-falls
- road works

Fortunately in most cases, it is not crucial to analyse every separate hazard. A proposed project may only address one or two of these hazards, so it is sufficient to examine its effects on these only. For example, strengthening a bridge may reduce the risk of being washed away in flood or damaged by earthquake. However, it probably has little effect on closures due to rock-falls or snowstorms, so they can be ignored in the analysis. The exception will generally be in the provision of new links, where consideration of a wide range of hazards may be needed to assess the effect on the network as a whole.

Additionally, a hazard may only be of significance along some links, and can be reasonably ignored on the others. For example, in a network with two routes, one along a river and one at high elevation, the latter can probably be ignored for flooding calculations.

Potential link reliability projects fall into the following categories:

- New links: these are the most complex to analyse because a larger range of hazards may need to be assessed over a number of links.
- Improved link, minimising likelihood of closures, e.g. strengthening a bridge against earthquake or flood damage.
- Improved link, minimising costs of closure event, e.g. improving an alternative route to increase capacity.
- Improved link, minimising route restrictions, e.g. upgrading a route to allow larger vehicles along it.

In all cases, the question to be answered is *how does it improve the overall expected costs of the network?*

Basic link reliability project analysis requires (above normal inputs):

- extra time/distance for detouring,
- probabilities of link closure with/without the project,
- likely cost of delays, and
- origins/destinations of travellers.

More detailed analysis of a project also requires:

- correlation of closures due to different hazards,
- reductions in expected route closure due to project,
- probability of synchronous closure of alternatives routes, and
- likely traffic flows diverted by closure.

There are a number of considerations for when to consider link reliability. Project cost could be seen as a useful criterion. Transfund uses construction cost bands for other evaluations, e.g. the use of simplified procedures for projects < $400,000 in costs. Arguably though, link reliability methods should be available for any project that can obtain reasonable benefits from it.

The relative redundancy inherent in the roading network also needs to be considered. The simple analysis in Section 3.2.1 suggested that network reliability is only worthwhile for links where there are *two or fewer* alternative routes. The definition of "alternative routes" may need clarifying; ideally, it should only include realistic alternatives rather than every technically possible option. For example, a closure of SH73 near Arthurs Pass may see SH7 through Lewis Pass become a viable cross-alpine option, but SH6 via Haast Pass may be impractical for travellers. This of course depends largely on the origins & destinations of the traffic, which will vary. For project evaluation purposes, it may be possible to specify conditions like:

(Alternative route Travel-time) < 2 × (Default Travel-time) for >50% of traffic

However, it is likely that some valid cases don't meet this criterion. Therefore, the selection should probably be left to the analyst.

Large sections of urban networks may generally not be affected by link reliability because of the considerable redundancy built into the network. However, strategic links such as bridges within an urban network may need to consider it.

If traffic and closure are both seasonal, then analysis of closure costs can't be made on AADT. Tourist routes and snow-affected areas are two examples. If, for example, there is a risk of snow closure for five months each year, then only the traffic costs for that part of the year can be assessed for benefits to projects.

Future traffic benefits also depend on the road being open:

$$\text{Expected Traffic in year } t = (\text{NormalTraffic}_t) \times [1 - P(\text{closure}_t) \times (\text{ClosureDays})/365] \quad (28)$$

In theory, this should apply to all projects on routes subject to closure. However, the expected effect in most cases is probably negligible.

The analysis must also consider the "weakest link"; it is no good improving a section of road, if another section of road will still limit the availability of the route.

For height/weight/length restrictions, one could assume that desire to use a restricted route will require either diversions to less restricted routes or, where possible, more trips using vehicles with smaller (i.e. acceptable) dimensions. For example, from the National Traffic Database (Works Consultancy 1996), the following gives the typical weight distributions for medium/heavy commercial vehicles on rural strategic routes:

**Table 3.2 Weight distribution of Commercial Vehicles on Rural Strategic Routes**

| Weight (kg) | % of CVs less than Weight |
|---|---|
| 48000 | 99.67% |
| 46000 | 99.11% |
| 44000 | 98.61% |
| 42000 | 97.68% |
| 40000 | 95.79% |
| 38000 | 95.20% |
| 36000 | 93.18% |
| 34000 | 92.06% |
| 32000 | 90.47% |
| 30000 | 89.17% |

Accordingly, if a bridge or other structure is rated for less than maximum loads, then the tonnage carried by heavier vehicles needs to be distributed among more vehicles that meet the weight requirement. This increases the number of trips made and subsequently the total travel time costs on the route for all vehicles. Table 3.3 calculates a factor that could be applied to scale the number of heavy vehicle trips to account for this.

**Table 3.3 Additional Vehicles required for given Weight Restriction**

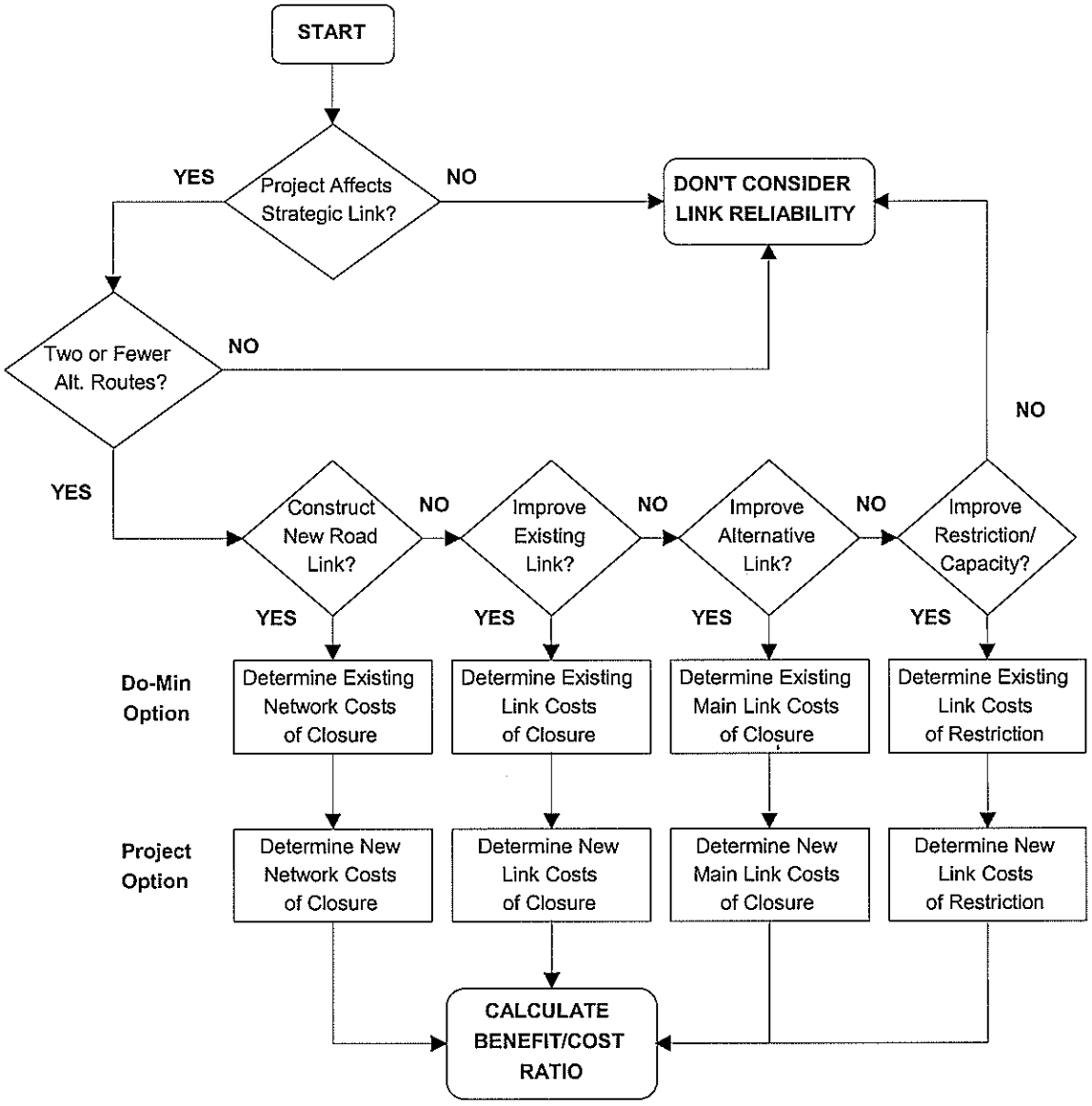
| Maximum Weight (kg) | Average Weight of Overweight Vehicles | Factor: Max.Wgt Veh Trips / O'weight Veh Trips |
|---|---|---|
| 48000 | 49555 | 1.032 |
| 46000 | 48173 | 1.047 |
| 44000 | 47333 | 1.076 |
| 42000 | 46561 | 1.109 |
| 40000 | 44548 | 1.114 |
| 38000 | 43672 | 1.149 |
| 36000 | 42431 | 1.179 |
| 34000 | 41847 | 1.231 |
| 32000 | 40603 | 1.269 |
| 30000 | 39831 | 1.328 |

The alternative is for the larger vehicles to take an alternative route if feasible. So the analyst must assess which is the likely optimal scenario (or perhaps assume a combination of both approaches)

### 3.4.1 Decision Flowchart for Project Evaluation

Figure 3.9 suggests a simple procedure for determining when to consider link reliability in project evaluation.

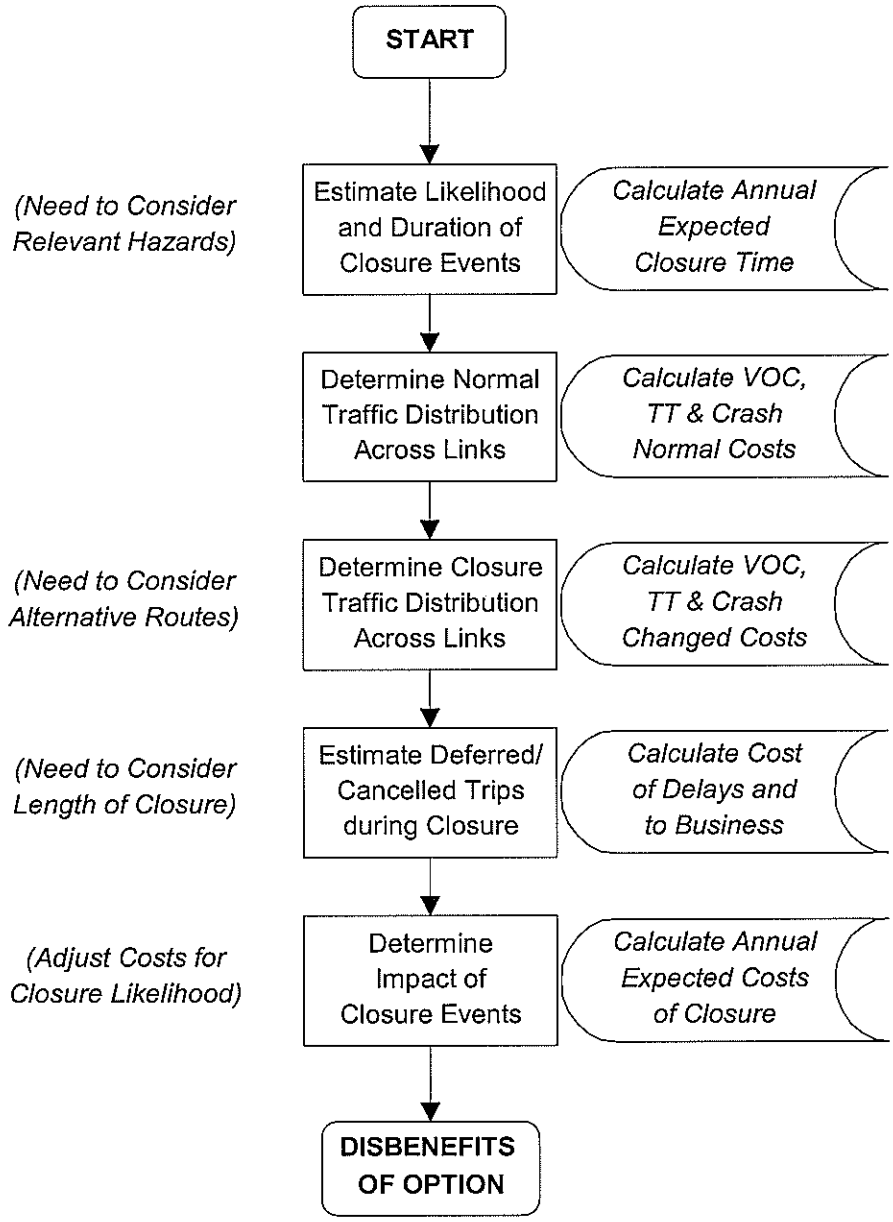
**Figure 3.9 Link Reliability Decision Flowchart**




The other possible requirement before considering link reliability is a minimum capital cost for a project. This ensures that extra effort is not undertaken on projects where little expenditure (and probably relatively little benefit) is expected.

Having established that link reliability is to be considered, Figure 3.10 summarises the steps in calculating costs of closure for either the do-minimum or project option. The "costs" are actually disbenefits, in terms of effects on travellers and businesses. There may also be a change in physical restoration/maintenance costs (e.g. less likely to need reinstatement) that should also be evaluated.

**Figure 3.10 Calculation of Option Link Reliability Costs**




Although the two previous diagrams refer to closures, they could arguably also apply to any degradation of a link, such as a reduction in capacity.

## 3.5 Examples of Link Reliability

Some simple scenarios have been developed to provide some examples of how basic reliability calculations could be incorporated into project evaluation. Some of the costs are for example only; reference should be made to the current PEM for values relevant to other projects. To simplify calculations, consideration of accident costs has also been ignored.

**Example 1:**

*A highway route regularly suffers from flooding. The probability/impact likelihood has been assessed below:*

| *Duration of Closure* | *Return Period* |
|---|---|
| *6 hrs* | *2 years* |
| *12 hrs* | *5 years* |
| *24 hrs* | *10 years* |

*The route takes 40 minutes to travel and has an AADT of 4000 vpd. During closures, an alternative route (at higher ground) takes 80 mins to travel and an extra 50 km. Restoration and traffic control work costs an average of $500 an hour while the road is closed.*

*Proposed river works will reduce the flood risk as given below:*

| *Duration of Closure* | *Return Period* |
|---|---|
| *6 hrs* | *10 years* |
| *12 hrs* | *30 years* |
| *24 hrs* | *negligible* |

Existing annual closure duration = 6 × (1/2-1/5) + 12 × (1/5-1/10) + 24 × (1/10) = 5.4 hrs/yr

⇒ expected annual maintenance costs = 5.4 × 500 = $2,700 / yr

Additional travel costs per vehicle = (TT costs for extra 40 mins) + (VOC costs for extra 50 km)

= 40/60 × $21.60 + 50 × $0.32 = $30.40 per vehicle

⇒ expected annual user costs = 5.4 × 4000/24 × $30.40 = $27,360 / yr

Proposed annual closure duration = 6 × (1/10-1/30) + 12 × (1/30) = 0.8 hrs/yr

⇒ expected annual maintenance costs = 0.8 × 500 = $400 / yr

⇒ expected annual user costs = 0.8 × 4000/24 × $30.40 = $4,053 / yr

⇒ expected annual cost savings = 2700 - 400 = $2,300 / yr

⇒ expected annual benefits = 27360 - 4053 = $23,307 / yr

These values then need to be discounted over the entire analysis period.

**Example 2:**

*A major route carrying 6000 vpd contains a weak bridge. It is predicted that an earthquake with a return period of 50 years would close the route for 10 days. Although an alternative route exists, 30% of the traffic would cancel their trips. There is also a 10% chance that the same earthquake would close the alternative route for the same duration, curtailing all trips. The additional TT/VOC costs in using the alternative route have been calculated as $55 per vehicle.*

*Structural improvements to the bridge and approaches are expected to protect it against an earthquake with a return period of up to 400 years and even then it would only be closed for 5 days. The same earthquake would have a 20% chance of closing the alternative route as well.*

Existing (do-min) case:

P(both major and alternative routes closed) = 1/50 × 10% = 0.002

P(major route only closed in any year) = 1/50 - 0.002 = 0.018

Cost to business of cancelled trips = ½ × $21.60 × 8hr × 30% = $25.92 per veh

⇒ Expected annual user costs = (Business costs of both routes closed) + (Business/User costs of major route closed)

= ($25.92 × 6000 × 10) × 0.002 + ($25.92 × 6000 × 30% × 10 + $55 × 6000 × 70% × 10) × 0.018

= $53,088 / yr

Proposed improvements:

P(both major and alternative routes closed) = 1/400 × 20% = 0.0005

P(major route only closed in any year) = 1/400 - 0.0005 = 0.002

⇒ Expected annual user costs = (Business costs of both routes closed) + (Business/User costs of major route closed)

= ($25.92 × 6000 × 5) × 0.0005 + ($25.92 × 6000 × 30% × 5 + $55 × 6000 × 70% × 5) × 0.002

= $3,165 / yr

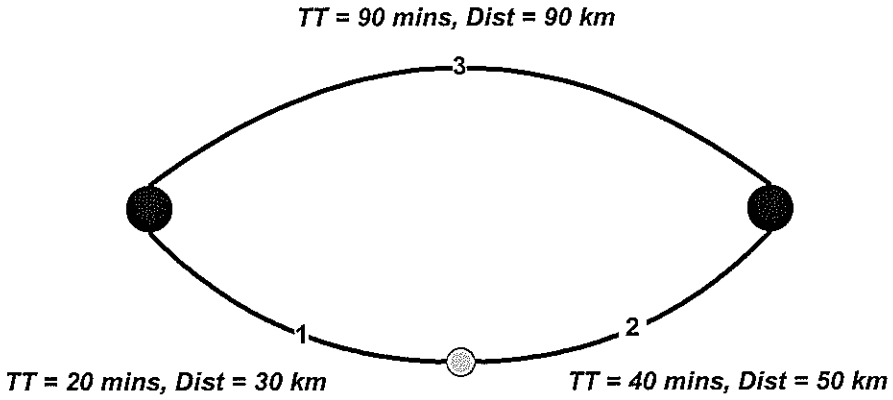
⇒ expected annual benefits = 53088 - 3165 = $49,923 / yr

These values then need to be discounted over the entire analysis period.

**Example 3:**

*An existing route (1-2) has an alternative route (3) as shown below:*

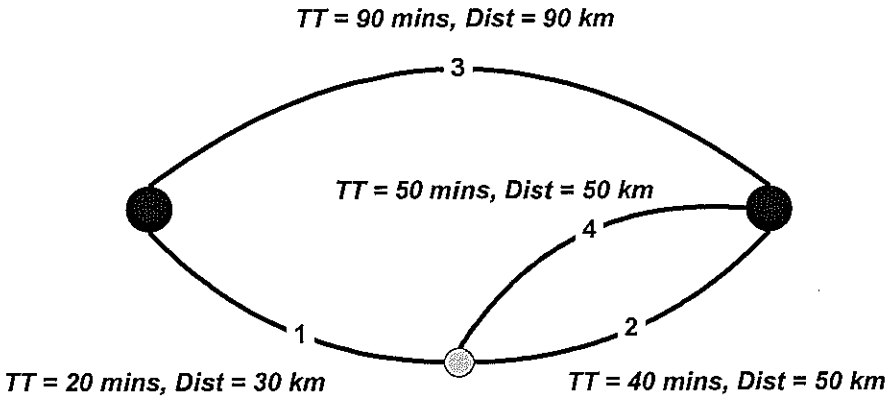
**Figure 3.11 Example 3: Existing Road Network**




*During normal traffic flows, 5000 vpd use links 1-2, while 500 vpd use link 3. The existing link 2 has a 5% chance of slip closures on any given day, while link 1 has no such hazard. Link 3 has only a 2% chance, although if link 2 is closed there is a 20% likelihood that it is also closed. If link 2 is closed then all of the traffic diverts via link 3. If they are both closed then all of the trips have to be cancelled.*

*A new link (4) is to be constructed as follows:*

**Figure 3.12 Example 3: Proposed Road Network**




*During normal traffic flows, 1000 vpd will now use link 4 instead of link 2. The new link has a 0.5% chance of slip closures on any given day, although if link 2 is closed there is a 5% likelihood that it is also closed. Link 3 is not expected to be affected by the likelihood of link 4 being closed. If link 2 is closed then all of the traffic diverts via link 4 (and vice versa); if both links are closed then all traffic diverts to link 3. All closures are assumed to last for the duration of the day, i.e. 24 hrs.*

Reliability of each link:

$r_1 = 1.000$, $r_2 = 0.950$, $r_3 = 0.980$, $r_4 = 0.995$

Dependence:

$P(f_3|f_2) = 20\% = 0.20$, $P(f_4|f_2) = 5\% = 0.05$

$P(r_3|r_2) = [r_3 - f_2 \times (1 - P(f_3|f_2))] / r_2$

$= [0.980 - 0.050 \times (1\text{-}0.20)] / 0.950$

$= 0.9895$

$P(r_4|r_2) = [r_4 - f_2 \times (1 - P(f_4|f_2))] / r_2$

$= [0.995 - 0.050 \times (1\text{-}0.05)] / 0.950$

$= 0.9974$

<u>Existing</u> overall reliability:

$R = r_{12} + r_3 - (r_{12} \times P(r_3|r_{12}))$

Because $r_1 = 1$, then $r_{12} = r_2$ and $P(r_3|r_{12}) = P(r_3|r_2)$

$\Rightarrow R = 0.950 + 0.980 - (0.950 \times 0.9895)$

$= 0.9900$

$\Rightarrow$ chance of total network closure = 1.00%

$\Rightarrow$ chance of link 2 closed only = 4.00%

$\Rightarrow$ chance of link 3 closed only = 1.00%

$\Rightarrow$ chance of all routes open = 94.00%

For each combination of closures, can now determine user and business costs and, from that, expected annual costs (not calculated here).

With new link:

$R = r_{124} + r_3 - (r_{124} \times P(r_3|r_{124}))$

Because $r_1 = 1$, then $r_{124} = r_{24}$ and $P(r_3|r_{124}) = P(r_3|r_{24})$

$\Rightarrow r_{24} = r_2 + r_4 - (r_2 \times P(r_4|r_2))$

$= 0.950 + 0.995 - (0.950 \times 0.9974)$

$= 0.9975$

Because link 3 is not dependent on link 4, $P(f_3|f_{24}) = P(f_3|f_2)$

$P(r_3|r_{24}) = [r_3 - f_{24} \times (1 - P(f_3|f_{24}))] / r_{24}$

$= [0.980 - 0.050 \times 0.005 \times (1\text{-}0.20)] / 0.9975$

$= 0.9822$

Can then apply to overall network reliability:

$\Rightarrow R = 0.9975 + 0.980 - (0.9975 \times 0.9822)$

$= 0.9977$

$\Rightarrow$ chance of total network closure = 0.23%

For each combination of closures, we can now determine user and business costs and, from that, expected annual costs (not calculated here). Then overall benefits can be ascertained.

## 3.6 Sample Worksheets for Link Reliability

The following pages provide some draft worksheets for project evaluation, based on the findings of this research and other reviewed work. These have been applied in Appendix A.3 to the above examples to demonstrate how they could be used.

The worksheets are particularly designed for "simple" closure situations, i.e. where a project will affect the likelihood or impacts of closures to a single link. Some modification to the worksheets may be necessary to allow for more complex calculations of link reliability. To minimise duplication, reference is also made to the existing PEM worksheets for calculating travel time, VOC, and accident costs.

**WORKSHEET LR1 – Assessment of Simple Closure Costs/Disbenefits**

PROJECT: _____

OPTION: _____

| *Totals from Worksheets LR2* | Annualised Closure *(AC)* | Annualised Cancellations *(PC)* | Annualised Delays *(AD)* | Annualised Maint. Costs *(AM)* |
|---|---|---|---|---|
| Hazard | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| Totals | hrs | hrs | hrs | $ |
| | (C) | (P) | (D) | (M) |

Closure Traffic Distribution Disbenefits:

| | | |
|---|---|---|
| Normal Hourly Road User Costs | $ | $(H)_N$ *from Worksheet LR3* |
| Closure Hourly Road User Costs | $ | $(H)_C$ *from Worksheet LR3* |
| Additional Hourly Closure Costs | $ | $(H)_{CN} = (H)_C - (H)_N$ |
| Annual Closure Road User Costs | $ | $(A)_C = (H)_{CN} \times (C)$ |

Cancelled Trips during Closure:

| | | |
|---|---|---|
| Normal Hourly Volume (veh/hr) | | *(V) on affected routes only* |
| Annual Trips Cancelled (hrs/yr) | | *(P) from table above* |
| Travel Time Cost ($/hr) | $ | *(T) from PEM Appendix A4* |
| Total Annual Business Costs | $ | $(A)_B = (P) \times 1.2 \times (T) \times (V)$ |

Delayed Trips during Closure:

| | | |
|---|---|---|
| Annual Vehicle Delays (hrs/yr) | | *(D) from table above* |
| Travel Time Cost ($/hr) | $ | *(T) from PEM Appendix A4* |
| Total Annual Delay Costs | $ | $(A)_D = (D) \times (T) \times (V)$ |

Other Costs of Closure *(show calculations separately)* $_____ per year = $(A)_O$

**Total Disbenefits of Option** = $(A)_C + (A)_B + (A)_D + (A)_O$ $_____ per year

**Total Maintenance Costs of Option** = *(M) from top table* $_____ per year

**WORKSHEET LR2 – Assessment of Hazard Closure Time & Maintenance/Repair Costs**

PROJECT: _____

OPTION: _____

Hazard: _____ *(Use one copy of this worksheet per hazard)*

| **Hazard Level** | $n$ | 1 | 2 | 3 | |
|---|---|---|---|---|---|
| **Return Period (yrs)** | $(a)_n < (a)_{n+1}$ | | | | |
| **Annual Probability** | $(b)_n = 1/(a)_n - 1/(a)_{n+1}$ | | | | |
| **Closure Duration (hrs)** | $(c)_n$ | | | | **TOTAL** |
| **Annualised Closure (hrs)** | $(d)_n = (b)_n \times (c)_n$ | | | | |
| **Cancelled Trips (%)** | $(e)_n$ | | | | *(AC)* |
| **Annualised Cancellations** | $(f)_n = (d)_n \times (e)_n$ | | | | |
| **Delayed Trips (%)** | $(g)_n$ | | | | *(PC)* |
| **Annualised Delays (hrs)** | $(h)_n = ½ \times (c)_n \times (d)_n \times (g)_n$ | | | | |
| | | | | | *(AD)* |

Maintenance/Repair Costs during closure:

| **Hazard Level** | $n$ | 1 | 2 | 3 | |
|---|---|---|---|---|---|
| **Maintenance Costs ($/hr)** | $(i)_n$ | | | | |
| **Cost of Repair Works ($)** | $(j)_n$ | | | | |
| **Maint Costs per Closure** | $(k)_n = (c)_n \times (i)_n$ | | | | **TOTAL** |
| **Annualised Maint Costs** | $(l)_n = (b)_n \times [(j)_n + (k)_n]$ | | | | $ |
| | | | | | *(AM)* |

**WORKSHEET LR3 – Hourly Road User Costs for Network**

PROJECT: _____

OPTION: _____

Traffic Distribution: Normal / Closure *(use one worksheet for each scenario)*

**Diagram of Network Flows:**

*(Show links and hourly flows. Number links for reference to table below)*

| Link No | Hourly Volume | Section Travel Time Costs / veh | Section Vehicle Operating Costs | Section Accident Costs / veh | Total Road User Costs |
|---|---|---|---|---|---|
| *(1)* | *(2)* | *(3) from PEM Worksheet A4.1* | *(4) from PEM Worksheet A5.1* | *(5) from PEM Worksheet A6.1* | *(6) = (2) × {(3)+(4)+(5)}* |
| | | | | | |
| | | | | | |
| | | | | | |
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| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | **TOTAL NETWORK COSTS PER HOUR *(H)*** | $ |

Transfer to Worksheet LR1

# 4. Conclusions

## 4.1 Project Evaluation Tools

The PEM does not currently provide many evaluation tools relating to risk and reliability. In summary:

a) Security of road access is only explicitly mentioned in the context of intangible NSFs and "isolation" effects, and not using tangible assessment means.

b) It does not define what is considered a "significant" risk to warrant the use of risk analysis (other than being mandatory for projects with >$10m capital cost).

c) No guidance is given on derivation of delay/detouring costs.

d) There is no specific example of link reliability being considered as part of the risk analysis section.

e) Only the simplified procedures for Structural Bridge Renewals contain any reference to the availability of alternative routes.

f) The "impacts that a project will have on the corridor or network" are only explicitly asked for in descriptive detail in the Full Procedures worksheets.

Arguably, these omissions are because most projects do not need to consider risk and reliability in their evaluation, and it can be quite a specialised topic.

## 4.2 Two Assessment Phases

There appear to be two distinct phases in assessing network reliability:

a) A partly qualitative assessment of the hazards facing the existing road network, to identify which links appear to be the most vulnerable to potential damage or closure. Because this exercise is largely at a strategic rather a project level, there is little potential for incorporating it into the PEM.

b) A quantitative evaluation of projects designed to improve the reliability of the existing road network. It is in this area that further detail and refinements could be provided in the PEM, for individual projects at least.

## 4.3 Assessing Link Reliability

The overall reliability of a highway link or network is affected when:

- a new link is constructed,
- the reliability of a link under various hazards is improved,
- the reliability of alternative routes is improved, or
- the capacity of a link is increased, either in terms of volume or vehicle restrictions.

For project evaluation, these factors should be considered when:

- the project is located on or affects the reliability of a strategic link,
- there are two or fewer alternative routes, or
- the costs or benefits of the project exceed a minimal level to be determined.

A suggested methodology using decision charts and worksheets has been drafted to trial link reliability techniques on such projects.

# 5. Recommendations

This report has outlined some possible techniques for evaluating link reliability. The next step is to apply these techniques in the evaluation of some projects (either already evaluated traditionally or for future work not yet evaluated). The recommended steps are:

- Further refine the draft worksheets presented in Section 3.6, perhaps using previous project risk evaluations for comparison.
- Use the worksheets for evaluation of current or future projects to identify the benefits likely from this analysis.
- Assuming that the benefits identified are shown to be significant (in terms of their effect on BCRs), incorporate the worksheets (with any modifications identified) into the PEM procedures.

## 5.1 Further Research

A number of points were raised that merit further investigation:

- One problem highlighted with closures is assessing the change in trip patterns. In many cases, not all of the traffic will delay or divert. Therefore, further work into the elasticities of closure is needed. The ideal approach would be to take some traffic count data on alternative routes during closure events and compare it with "normal" flows. Care needs to be taken, however, given the likely temporal variations during the closure.

  Obviously, the very nature of hazards mean that traffic surveys cannot be planned in advance, particularly for short closures. However a programme could be set up to place some counting equipment on "standby" over a period of time with the aim of getting it on site as fast as possible.

  To assist in determining elasticities, an alternative approach would be to survey users on their:

  - time/cost to defer
  - time/cost to detour
  - time/cost to cancel
- The effect of closures on businesses needs further investigation. A number of reviewed studies made various assumptions on this, but a more direct examination, perhaps by means of willingness-to-pay surveys, may be necessary. As NSFs become used in project evaluations, a record of some valuations may also become available.
- As discussed in Section 2.3, the closure costs associated with both crashes and road works have not been investigated fully here in New Zealand. Further work is needed to quantify these effects and incorporate them in project evaluations.

The findings from research in these areas may be subsequently incorporated into any link reliability evaluation methodology developed.

# 6. References

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# Appendices

## A.1 Some Methods for Establishing Failure Rates

The following extracts provide some practical examples of how various hazards have been assessed in New Zealand. Please note that they are not definitive, and should be adjusted to suit different situations.

### A.1.1 Closure due to Ice

Dalziell *et al* (1999) examined weather data for the Desert Road and attempted to correlate this with closures due to ice. Because the nearest weather station was at Waiouru at a slightly lower altitude, the recorded temperatures had to be adjusted down by about 2°C to account for this variation.

For any specified day with daily minimum and maximum temperatures $T_{min}$ & $T_{max}$ and relative humidity RH, there was a 25% chance of closure due to ice when:

$$(T_{min} < 0°) \text{ AND } (T_{max} < 8°) \text{ AND } (RH > 84\%)$$

If not all of these criteria were met then there was virtually no chance of closure.

Given data from local weather stations, a "weighted" average for temperatures at roadway locations can be obtained by the following steps (based on Ball *et al* 1999):

a) Let the road site altitude be H metres and northern and eastern NZMG coordinates N and E respectively; the temperature (minimum, mean or maximum) to be calculated is T.

b) Select weather stations to be used for each location, usually by limiting selection to those within a specified radius (e.g. 50 km). Ideally there should be at least four stations selected. Let the corresponding values for met station i be $H_i$, $N_i$ and $E_i$ with a corresponding temperature $T_i$ .

c) For each weather station, adjust the temperature readings to be equivalent to the roadway altitude (Transit NZ have altitude data available for all reference stations). Calculate station temperatures, $\tau i$, adjusted to the altitude of the road site, as follows:

$$\tau_i = T_i - k\ (H - H_i) \qquad (1)$$

where k = 0.00552 for minimum temperatures

0.00516 for mean temperatures

0.00490 for maximum temperatures

d) Calculate the distance, Si , from the road site to the met station:

$$S_i = \sqrt{(H - H_i)^2 + (N - N_i)^2 + (E - E_i)^2} \qquad (2)$$

e) Calculate the weighted average of temperature readings, T, for the road position from the surrounding weather stations:

$$T = \sum_{i=1}^{n} \frac{\tau_i / S_i}{\sum_{j=1}^{n} \frac{1}{S_j}} \tag{3}$$

Note that for just two met stations the equation reduces to

$$T = \frac{S_2}{S_1 + S_2}\tau_1 + \frac{S_1}{S_1 + S_2}\tau_2 \quad \text{i.e. a linear interpolation.} \tag{4}$$

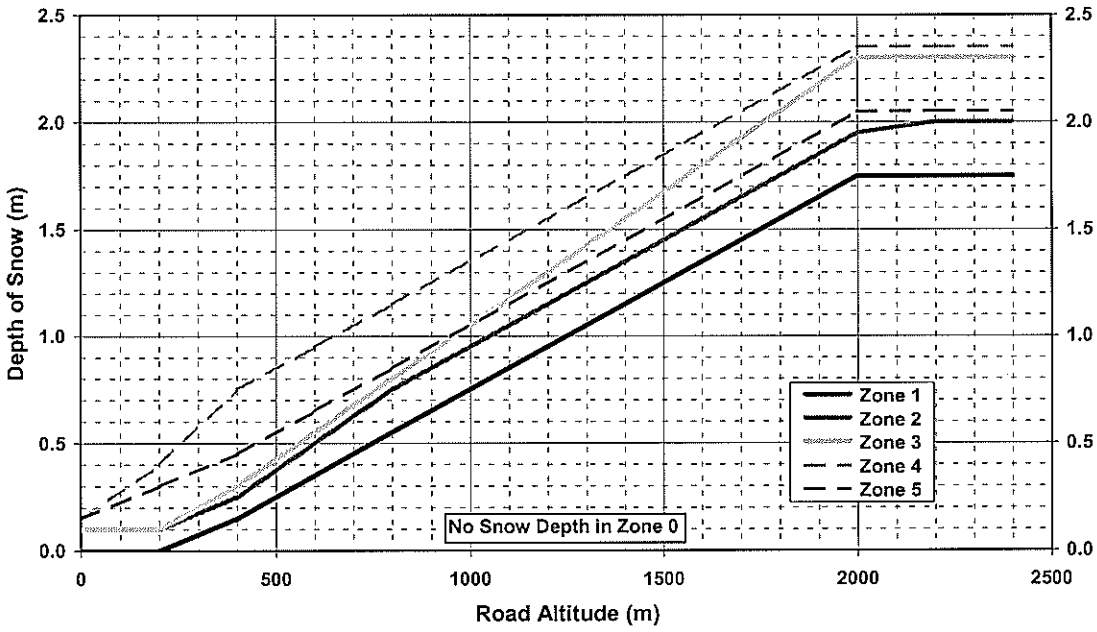
### A.1.2 Closure due to Snow

Montgomery Watson (1998) adapted the snow load procedures from the New Zealand Loadings Code NZS4203 (Standards NZ 1992). For a particular highway link in a given snow zone, as specified in Figure A.2, the maximum altitude should be determined as well as the length of highway at that altitude. Figure A.1 then gives the maximum expected snow depth for a 50-year return period at the specified altitude. Similar depths can also be calculated for 25-year and 100-year return periods:

$$\text{Depth}_{25\text{-yr}} = \text{Depth}_{50\text{-yr}} \times 0.63 \tag{5}$$

$$\text{Depth}_{100\text{-yr}} = \text{Depth}_{50\text{-yr}} \times 1.25 \tag{6}$$

**Figure A.1 Depth of Snow expected in 50-Year Return Period**




Expected closure times can then be established for various depths of snow, while maintenance crews clear it e.g.

- 0.5m deep: 0.2 hrs/km
- 1.0m deep: 0.5 hrs/km
- 1.5m deep: 1.0 hrs/km

### A.1.3 Closure due to Seismic Instability

Montgomery Watson (1998) adapted the seismic load procedures from the New Zealand Loadings Code NZS4203 (Standards NZ 1992). For a particular highway link in a given

seismic zone, Z, as specified in Figure A.2, each slope should be identified as either "stable" (factor of safety ≈ 1.9), "marginal" (FOS ≈ 1.3), or "unstable" (FOS ≈ 1.1). The return period for a given percentage, F%, of slopes that fail is then calculated by:

$$\text{Return Period } RP_{F\%} = 10^{[2.65 - (0.4 - A / Z) \times 4.24]} \quad (7)$$

where $A$ is the triggering ground acceleration (as a proportion of $g$) for a given stability and percentage of failures, as listed in Table A.1.

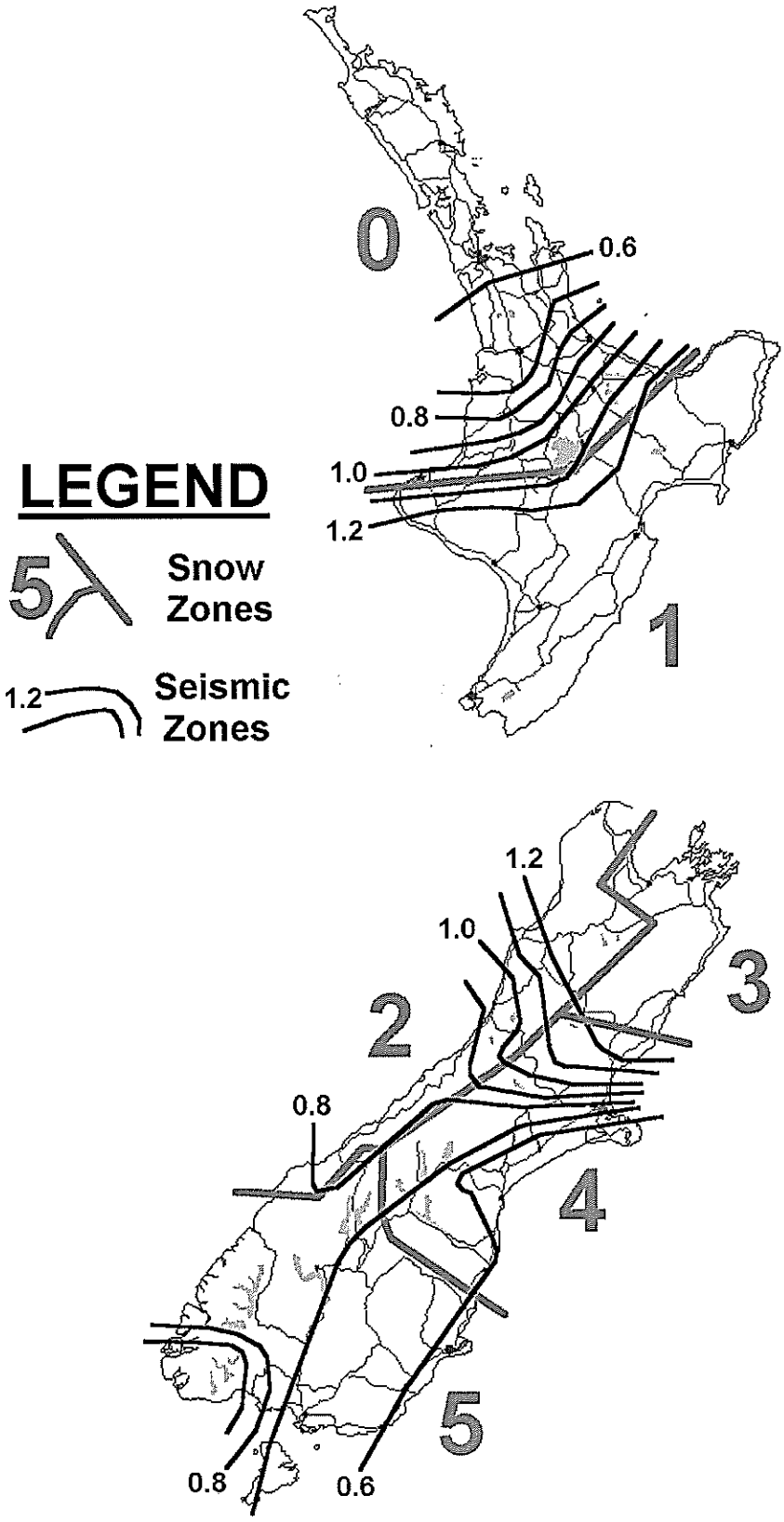
**Table A.1 Peak Ground Acceleration to trigger Slope Instability**

| Stability | 5% Fail | 50% Fail | 70% Fail |
|---|---|---|---|
| Unstable | 0.07 | 0.11 | 0.31 |
| Marginal | 0.15 | 0.24 | 0.47 |
| Stable | 0.35 | 0.55 | 0.79 |

By then assessing the expected closure time for each slope, the expected annual closure time for each slope can then be calculated:

$$\text{Expected Annual Hrs} = [.05 / RP_{5\%} + .50 / RP_{50\%} + .70 / RP_{70\%}] \times \text{Closure Time (hrs)} \quad (8)$$

**Figure A.2 Seismic and Snow Zones for New Zealand**

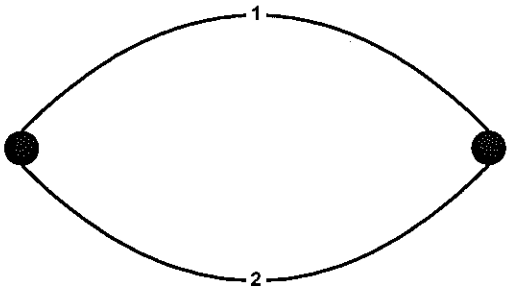



(adapted from NZS 4203: 1992)

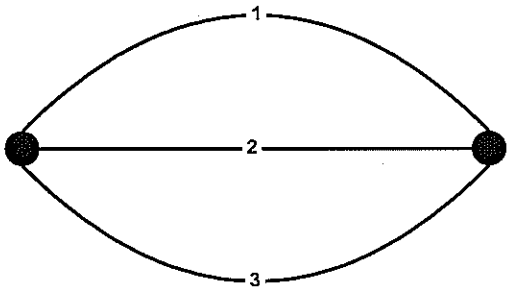
## A.2 Reliabilities for Various Link Networks

Note: the following layouts also give the same reliabilities when mirrored.

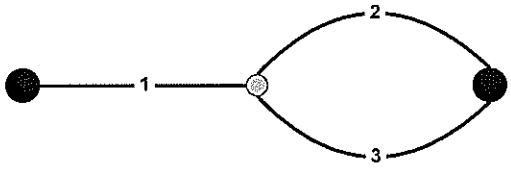
$R = S\{1,2\}$
$= r_1 \times r_2$



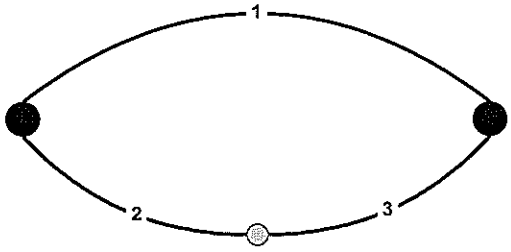

$R = P\{1,2\}$
$= 1 - ((1-r_1) \times (1-r_2))$



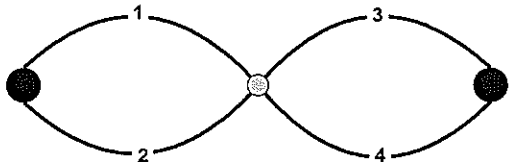

$R = P\{1,2,3\}$
$= 1 - ((1-r_1) \times (1-r_2) \times (1-r_3))$



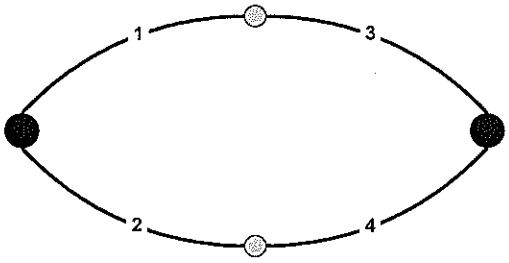

$R = S\{1,P\{2,3\}\}$
$= r_1 \times (1 - ((1-r_2) \times (1-r_3)))$



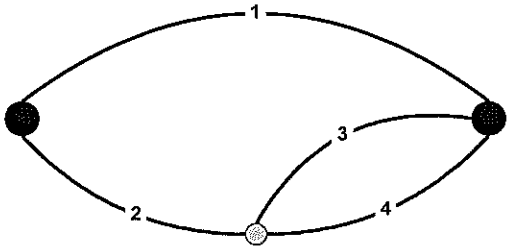

$R = P\{1,S\{2,3\}\}$
$= 1-((1-r_1) \times (1-(r_2 \times r_3)))$



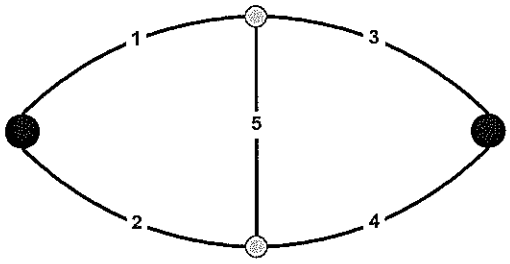

$R = S\{P\{1,2\},P\{3,4\}\}$
$= (1 - ((1-r_1) \times (1-r_2))) \times (1 - ((1-r_3) \times (1-r_4)))$




$$R = P\{S\{1,3\},S\{2,4\}\}$$
$$= 1-(\,(1-(r_1 \times r_3)) \times (1-(r_2 \times r_4)))$$




$$R = P\{1,S\{2,P\{3,4\}\}\}$$
$$= 1-((1-r_1) \times (1-(r_2 \times (1-((1-r_3) \times (1-r_4))))))$$




$$R = r_5 \times S\{P\{1,2\},P\{3,4\}\}$$
$$+ (1-r_5) \times P\{S\{1,3\},S\{2,4\}\}$$

## A.3 Application of Sample Worksheets to Example Project

The following pages apply the worksheets of Section 3.6 to the examples from Section 3.5. Note that as each example demonstrates different aspects of link reliability evaluation, only parts of these examples have been provided for illustration only.

**WORKSHEET LR1 – Assessment of Simple Closure Costs/Disbenefits**

PROJECT: *Example 1*

OPTION: *Existing Situation (Do Minimum)*

| *Totals from Worksheets LR2* | Annualised Closure *(AC)* | Annualised Cancellations *(PC)* | Annualised Delays *(AD)* | Annualised Maint. Costs *(AM)* |
|---|---|---|---|---|
| Hazard | | | | |
| *Flooding* | *5.4* | - | - | *2700* |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| Totals | *5.4* hrs | *0* hrs | *0* hrs | $ *2700* |
| | (C) | (P) | (D) | (M) |

Closure Traffic Distribution Disbenefits:

| | | |
|---|---|---|
| Normal Hourly Road User Costs | $ *4533.3* | *$(H)_N$ from Worksheet LR3* |
| Closure Hourly Road User Costs | $ *9600.0* | *$(H)_C$ from Worksheet LR3* |
| Additional Hourly Closure Costs | $ *5066.7* | $(H)_{CN} = (H)_C - (H)_N$ |
| Annual Closure Road User Costs | $ *27 360* | $(A)_C = (H)_{CN} \times (C)$ |

Cancelled Trips during Closure:

| | | |
|---|---|---|
| Normal Hourly Volume (veh/hr) | *170* | *(V) on affected routes only* |
| Annual Trips Cancelled (hrs/yr) | *0* | *(P) from table above* |
| Travel Time Cost ($/hr) | $ - | *(T) from PEM Appendix A4* |
| Total Annual Business Costs | $ *0* | $(A)_B = (P) \times 1.2 \times (T) \times (V)$ |

Delayed Trips during Closure:

| | | |
|---|---|---|
| Annual Vehicle Delays (hrs/yr) | *0* | *(D) from table above* |
| Travel Time Cost ($/hr) | $ - | *(T) from PEM Appendix A4* |
| Total Annual Delay Costs | $ *0* | $(A)_D = (D) \times (T) \times (V)$ |

Other Costs of Closure *(show calculations separately)* $ *0* per year = $(A)_O$

**Total Disbenefits of Option** = $(A)_C + (A)_B + (A)_D + (A)_O$ $ *27360* per year

**Total Maintenance Costs of Option** = *(M) from top table* $ *2700* per year

**WORKSHEET LR2 – Assessment of Hazard Closure Time & Maintenance/Repair Costs**

PROJECT: *Example 2*

OPTION: *Existing Situation (Do Minimum)*

Hazard: *Earthquake*

*(Use one copy of this worksheet per hazard)*

| **Hazard Level** | $n$ | 1 | 2 | 3 | |
|---|---|---|---|---|---|
| **Return Period (yrs)** | $(a)_n < (a)_{n+1}$ | 50 | 500 | | |
| **Annual Probability** | $(b)_n = 1/(a)_n - 1/(a)_{n+1}$ | 0.018 | 0.002 | | |
| **Closure Duration (hrs)** | $(c)_n$ | 240 | 240 | | **TOTAL** |
| **Annualised Closure (hrs)** | $(d)_n = (b)_n \times (c)_n$ | 4.32 | 0.48 | | 4.8 |
| **Cancelled Trips (%)** | $(e)_n$ | 30% | 100% | | *(AC)* |
| **Annualised Cancellations** | $(f)_n = (d)_n \times (e)_n$ | 1.296 | 0.48 | | 1.776 |
| **Delayed Trips (%)** | $(g)_n$ | 0% | 0% | | *(PC)* |
| **Annualised Delays (hrs)** | $(h)_n = ½ \times (c)_n \times (d)_n \times (g)_n$ | - | - | | |
| | | | | | *(AD)* |

Maintenance/Repair Costs during closure:

| **Hazard Level** | $n$ | 1 | 2 | 3 | |
|---|---|---|---|---|---|
| **Maintenance Costs ($/hr)** | $(i)_n$ | 200 | 300 | | |
| **Cost of Repair Works ($)** | $(j)_n$ | 200 000 | 240 000 | | |
| **Maint Costs per Closure** | $(k)_n = (c)_n \times (i)_n$ | 48 000 | 72 000 | | **TOTAL** |
| **Annualised Maint Costs** | $(l)_n = (b)_n \times [(j)_n + (k)_n]$ | 4464 | 624 | | $ 5088 |
| | | | | | *(AM)* |

*Note: Hazard Level 2 = Alternative Route Closed Too*

**WORKSHEET LR3 – Hourly Road User Costs for Network**

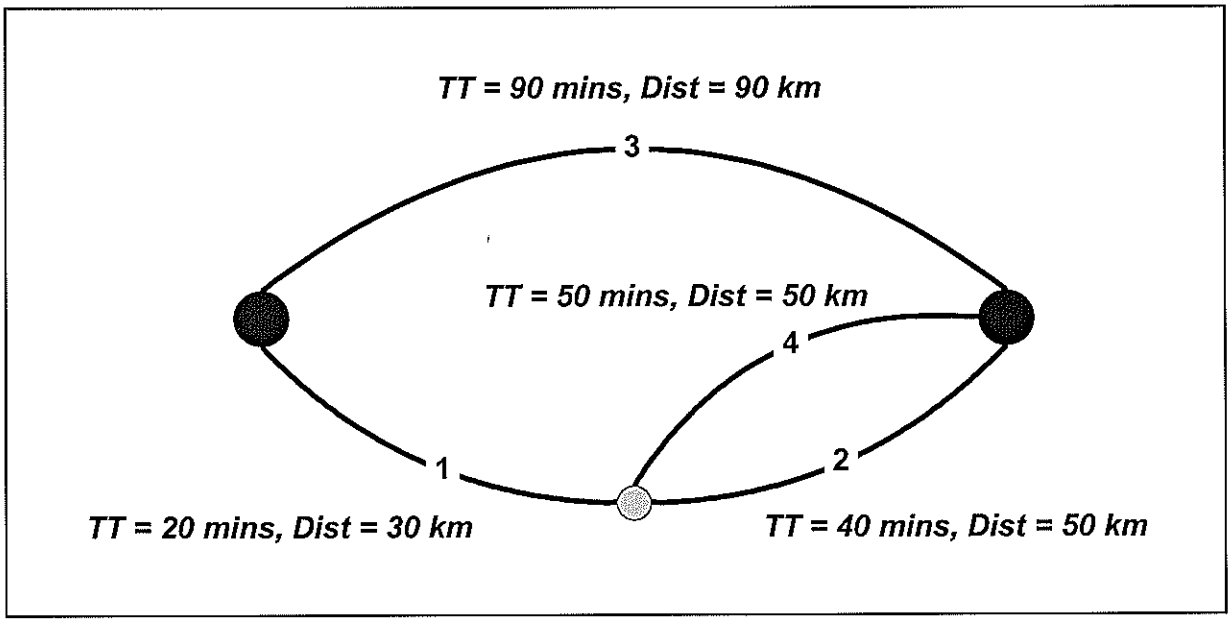
PROJECT: *Example 3*

OPTION: *Build Link 4*

Traffic Distribution: Normal / ~~Closure~~ *(use one worksheet for each scenario)*

**Diagram of Network Flows:**

*(Show links and hourly flows. Number links for reference to table below)*




| Link No | Hourly Volume | Section Travel Time Costs / veh | Section Vehicle Operating Costs | Section Accident Costs / veh | Total Road User Costs |
|---|---|---|---|---|---|
| *(1)* | *(2)* | *(3) from PEM Worksheet A4.1* | *(4) from PEM Worksheet A5.1* | *(5) from PEM Worksheet A6.1* | *(6) = (2) × {(3)+(4)+(5)}* |
| *1* | *250* | *$7.20* | *$9.60* | *$3.45* | *$5062* |
| *2* | *200* | *$14.40* | *$16.00* | *$5.75* | *$7230* |
| *3* | *25* | *$32.40* | *$28.80* | *$16.56* | *$1944* |
| *4* | *50* | *$18.00* | *$16.00* | *$5.06* | *$1953* |
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**TOTAL NETWORK COSTS PER HOUR *(H)*** $ *16 189*

Transfer to Worksheet LR1