Assessing and Mitigating the Impacts of Road Network Unreliability

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Synopsis

Road network unreliability can arise from variations in the supply and/or demand for transport. In major urban areas, where the networks are typically dense and congested, both supply and demand variations occur. Although they are typically of relatively short duration, the social and economic impacts can be substantial. In rural areas, where the networks are typically sparse and uncongested, demand variations are generally not important, but supply variations, which are typically of relatively long duration, can have substantial social and economic impacts. Some countries are actively pursuing methods for reducing those economic impacts. In New Zealand (NZ), for instance, procedures for the economic appraisal of transport projects have recently been extended to include changes in the variability of travel times, with a view to improving the reliability of urban networks and transport services. The reliability of rural networks has also been receiving considerable attention, with the focus being on minimizing the social and economic impacts of network disruption associated with natural disasters, such as earthquakes, volcanic eruptions, storms and tsunamis.

This paper will describe and discuss the measures being taken in NZ to assess and mitigate the impacts of road network reliability, with particular attention to rural (or inter-urban) networks. Much of the work to date has involved the application of risk management techniques combined with scenario analyses, but a difficulty with this approach is deciding which scenarios should be included in the analysis. This difficulty may be overcome via a "walk-through scenario approach", which involves randomly generating hazard events over a suitable analysis period. This technique does rely upon the probability of hazard events being known, along with correlations between the occurrence of such events (e.g. the probability of a tsunami depends upon whether an earthquake has occurred and the characteristics of that earthquake). An advantage of this technique is that it enables an assessment of whether the greater risk comes from frequent, minor-consequence events, or from rare, major-consequence events (i.e. it does not focus on "worst-case" scenarios and it avoids the potential for misallocating resources). A recent study has concluded that a "walk-through scenario" approach should be employed for an all-hazards risk assessment of the NZ State Highway network, to provide a basis for prioritizing risk management investment in the network.

Recent years have seen an upsurge of attention to Civil Defence and Emergency Management (CDEM) in NZ. This is seen as involving four phases: reduction (i.e. identifying and reducing risks via infrastructure improvement), readiness (i.e. training civil defence staff and installing warning systems), response (i.e. reacting to emergency situation in the short-term), and recovery (i.e. minimizing the socio-economic impacts in the long-term). This paper will also outline a study of how NZ organisations, including the State Highway Authority (Transit NZ), prepare for and react to hazard events, so as to enable full recovery as quickly as practicable.

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INTRODUCTION

Historical Review

During the last 20-30 years there has been growing concern about 'lifeline systems' (e.g. water supply, energy supply, sewage disposal, communication, and transportation systems) and their vulnerability to damage and disruption during major disasters, such as earthquakes, tsunamis and storms. While lifeline engineering initially focused on considering each lifeline system in isolation, a study of the inter-dependence of lifeline systems (Centre for Advanced Engineering, 1991; Hopkins et al. 1991) found that the transportation system is the most important lifeline system, because the restoration of virtually all other lifeline systems depends on people and equipment being able to move to the sites where damage has occurred, and damage to the transportation system inhibits repairs to the other lifeline systems.

Lifeline engineering also initially focused on reducing the expected costs of repairs to lifeline systems, through relocating the services and strengthening selected components. However, these costs are likely to be smaller than the other costs, such as the cost of temporary works and increased user costs during the period of disruption. For instance, one study found that the cost of temporary work (e.g. upgrading an alternative route for diverted vehicular traffic, construction of a temporary bridge to carry water, sewage, etc.) was 50% greater than the cost of replacing a highway bridge washed away during a storm (Works Consultancy Services 1990).

Yee et al. (1996) studied how the 1994 Los Angeles (Northridge) earthquake, which closed highways that carried some of the highest daily traffic volumes in the world, affected user costs. They found that even after the establishment of detours around closed highway facilities and carpool lanes, and the enhancement of rail and bus services, the cost of motorist delay associated with the closure of just one facility (Interstate Highway 10) was almost US$1 million per day.

This estimate of the increased user cost excluded the socio-economic costs due to the disruption of commercial traffic movements and business, and these costs are likely to be much greater than the direct cost of replacing damaged infrastructure. For instance, the business interruption losses resulting from the collapse of the World Trade Center buildings have been estimated [Münchener Rück, 2001] to "far exceed" the cost of the property losses (i.e. the cost of replacing the structures and the equipment and supplies in the structures).

The economies in developed countries depend heavily on their transportation systems, and that dependence is increasing due to the adoption of "just-in-time" production methods, which involve reducing the space and investment associated with goods storage and relying on a high quality transport service. Surveys of transportation system users (e.g. Parkhurst et al. [1992]) have shown that while the quality of service embraces a wide range of service attributes, one of the most important is reliability. Parkhurst et al. found that users commonly mentioned unreliability, and the consequent variability and unpredictability of travel times, as a negative service attribute. Hence, the reliability of transport networks is becoming an increasingly important issue.

Sources of Unreliability

Nicholson and Du [1997] suggest unreliability can be considered to arise from two distinctly different sources; demand (or flow) variations and supply (or capacity) variations. Figure 1 shows that for an arc with capacity x_{a0}, the travel time varies as a result of arc flow variation. The travel time varies about t_{a2} (corresponding to an arc flow v_a=v_{a2}), between a lower bound t_{a3} (corresponding to the lower bound arc flow v_{a3}) and an upper bound t_{a1} (corresponding to the upper bound arc flow v_{a1}). Figure 2 shows that for an arc with flow v_a^*, the travel time varies as a result of arc capacity variation. The travel time again varies about t_{a2} (corresponding to an arc capacity x_a=x_{a1}), between a lower bound t_{a3} (corresponding to the upper bound arc capacity x_{a0}) and an upper bound t_{a1} (corresponding to the lower bound arc capacity x_{a2}).

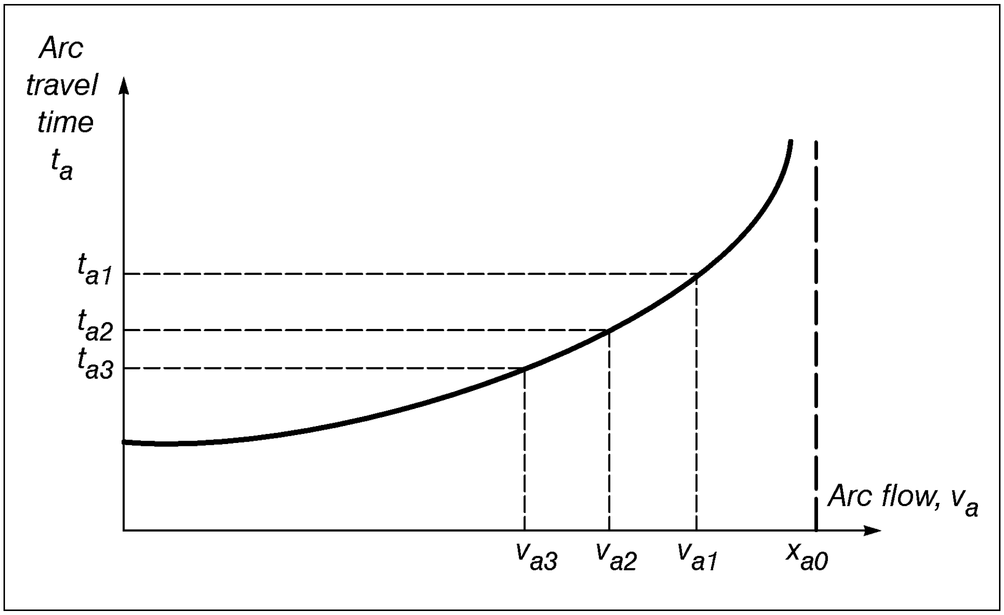

Figure 1: Arc Flow Variation

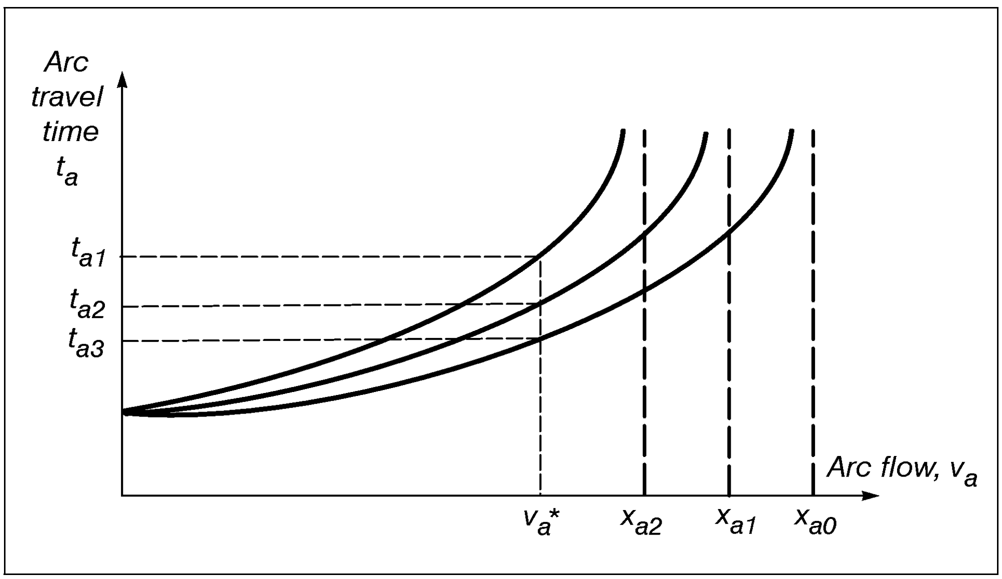

Figure 2: Arc Capacity Variation

In reality, travel time variation can arise from either or both sources, and it is not always an easy matter to identify the separate effects of flow and capacity variations. For instance, if an accident occurs during the early part of a peak period and results in a road being partly blocked, it may well be difficult to separate the effect of the capacity reduction and the increasing traffic flow. In major urban areas, where the networks are typically dense and congested, both supply and demand variations can readily occur. Although such variations in urban areas are typically of relatively short duration, the social and economic impacts can be substantial. In rural areas, however, where the networks are typically sparse and uncongested, demand variations are generally not important, but supply variations, which can well be of relatively long duration, can have substantial social and economic impacts.

The main focus of transportation network reliability research has been upon reducing the impact of arc capacity variations. This is probably because there are authorities that are responsible for managing transportation networks and are expected to minimise the frequency and consequence of such events. However, travel time variations associated with variations in travel demand are the result of decisions made by many individual travellers, and are thus less amenable to reduction via direct intervention.

In some countries (e.g. New Zealand), the reliability of rural networks has also been receiving considerable study, with the focus being on minimizing the social and economic impacts of network disruption associated with natural hazards (e.g. earthquakes, volcanic eruptions, storms and tsunamis), for which the duration of disruption may be measured in weeks or months. One such study is briefly described later. More recently, however, the reliability of urban networks has also been receiving much attention, and one such study is also briefly described later. Although the duration of disruption might be relatively short (i.e. measured in minutes or hours), the frequency of such events, and the number of users involved may well mean that the socio-economic impacts might exceed those of major disasters.

Mitigation Options

There are various methods for mitigating the effects of supply and/or demand variations and improving network reliability. They include [Nicholson and Du, 1994]:

- improving component reliability (e.g. replacing or strengthening bridges);
- improving the network configuration (e.g. constructing new links);
- having stand-by components, which are activated after degradation of the original component (e.g. Bailey bridges, emergency air-ferry services);
- monitoring critical components, to detect degradation and advise users of alternatives;
- undertaking regular preventive maintenance;
- identifying priorities for repairing degraded components to minimise the socio-economic impacts, and optimally deploying resources for repair work.

Lifeline engineering has traditionally focused upon the first option, but Goodwin [1992] suggested pursuing the second option. He proposed the concept of a “quality margin” in transport, akin to a margin of safety, suggesting that transport planners “should deliberately allow for spare capacity in the system, some redundancy — some inefficiency, in a sense — in order to enjoy benefits that are not measured by maximum production”. There is doubt, however, regarding the practicability of increasing reliability by providing spare capacity, because of the tendency for transportation system to function like queueing systems.

Queueing theory has been applied to the analysis of traffic flow at intersections and along links for many years (e.g. Gerlough and Huber [1975]), with the emphasis being upon estimating the mean travel time or delay for users. One of the simplest queueing theory models is the M/M/1 model, where traffic arrives according to a Poisson process (i.e. the headways between vehicles are negative exponentially distributed), the service times (i.e. the times spent at the head of the queue before a suitable gap occurs in the priority flow) are also negative exponentially distributed, and there is one service channel (i.e. one approach lane for the non-priority flow). According to Wolff [1988], for such a system the total travel time (i.e. the time from joining the queue until being able to join or cross the priority flow) will vary according to the negative exponential distribution, where the parameter is the mean service rate (μ) minus the mean arrival rate (λ), for $\lambda < \mu$. That is, the mean travel time equals $[1/(\mu-\lambda)]$ and the variance of the travel time equals $[1/(\mu-\lambda)^2]$. As the mean arrival rate (λ) increases and approaches the mean service rate (μ), both the mean travel time and the variance of the travel time increase towards infinity. It can be seen from the expressions that the variance will increase more rapidly than the mean.

Figure 3 shows how the mean and variance of the travel time increase as the traffic intensity ρ ($=\lambda/\mu$) increases. It can be seen in Figure 3 that the mean travel time starts to increase much more rapidly once the traffic intensity ρ exceeds about 80%, and it is thus common practice when designing transport facilities to define the practical capacity of such a system to be 80% of the theoretical capacity (e.g. Austroads [1988]). This implies a safety margin of 20%. It can also be seen in Figure 3 that for ρ less than 60%, the variance of the travel time is very similar to the mean travel time, but the variance starts to increase much more rapidly once the traffic intensity ρ exceeds about 60%. If one was to design to keep the ratio of the variance to the mean low (less than unity, say), to achieve a high level of reliability, the practical capacity would be only about 60% of the theoretical capacity. This implies that the safety margin should be about 40% (or about double that commonly used at present).

While it has been shown, for a simple M/M/1 queueing system, that the traffic intensity at which the travel time variance starts to increase rapidly is markedly lower than the traffic intensity at which the mean travel time starts to increase rapidly, it seems likely that this will also apply for the more complex queueing systems used for analysing some traffic flow situations.

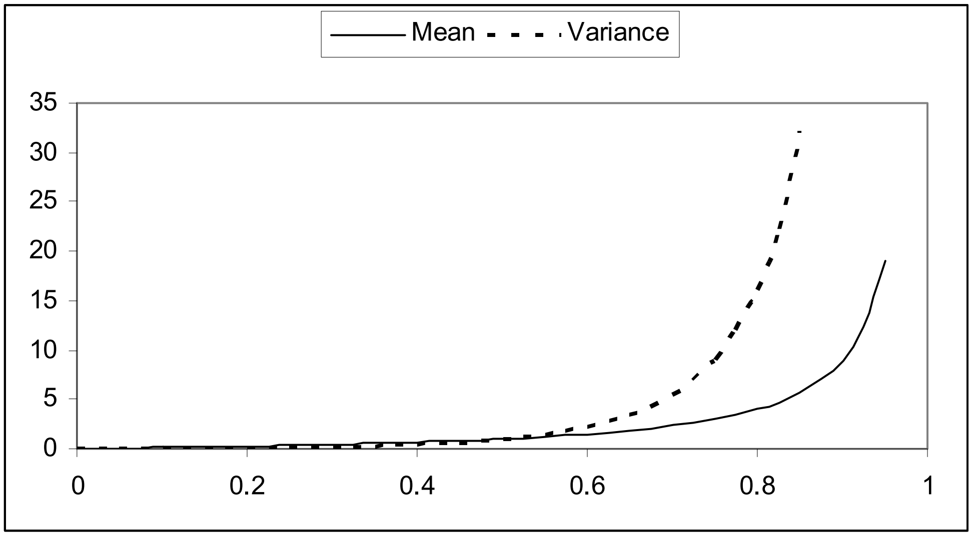

Figure 3: Mean and Variance of Travel Time Versus Traffic Intensity

The mean arrival and service rates reflect the demand and supply, respectively, while the travel time represents the average rather than the marginal travel cost. In the absence of a mechanism for ensuring the marginal travel cost equals the marginal utility, it is difficult to see how maintaining such a large safety margin as 40% could be achieved, as the provision of such a large margin will lead to lower mean travel times and thus greater usage. That is, designing for a large quality margin, as proposed by Goodwin [1992], is unlikely to lead to greater reliability, unless we can ensure equality of the marginal costs and utilities (via congestion pricing, say).

In New Zealand, it is common to categorise mitigation options as follows:

- reduction (i.e. identifying and reducing risks via infrastructure improvement);
- readiness (i.e. training civil defence staff and installing warning systems);
- response (i.e. reacting to emergency situation in the short-term);
- recovery (i.e. minimizing the socio-economic impacts in the long-term).

Reduction options (e.g. improving component reliability and network configuration, undertaking regular preventive maintenance) have been the primary focus of mitigation effort in the past, but there has recently been a shift towards readiness options (including deploying stand-by components for activation after degradation of the original component), response options (e.g. monitoring critical components and advising users of degradation and alternatives travel options), and recovery options (e.g. identifying priorities for repairing degraded components to minimise the socio-economic impacts).

INTER-URBAN HIGHWAY NETWORKS

Central North Island Network Study

This network includes the Desert Road section of State Highway 1, which is the main route between Wellington (the capital) and Auckland (the largest urban area), and carries the bulk of the traffic between those two cities (and between other urban areas). It is a two-lane two-way highway, carrying about 4000 vehicles/day, with about 15% being heavy commercial vehicles. The Desert Road is New Zealand's highest section of State Highway, reaching an elevation of 1130 metres above sea level, and it lies largely within a seismically active and ecologically-sensitive area, with three active volcanoes close by on the western side.

This study involved using standard risk evaluation and management methods, and the first step was to identify the hazards, which were found to be:

- snow and ice formation;
- ash fall during volcanic eruptions;
- lahar damage to roads and bridges;
- earthquake damage to roads and bridges;
- motor vehicle accidents.

The next step was to estimate, for each hazard, both the probability and the consequence of its occurrence. The consequence includes the cost of any remedial work (e.g. bridge repairs or replacement) and the economic cost borne by users whose travel is affected. The user costs will depend on the closure duration, as well as the availability of alternative routes and cost of diverting (or loss of utility if users cancel or postpone their travel).

It was necessary to derive a frequency distribution of closure duration for each hazard. This was done using a mixture of historical information about the probability of events and an understanding of the generating mechanisms of each of the hazards, plus Monte Carlo simulation (see Dalziell [1998] for details).

The closure costs depend on the reason for closure, because of correlation between route conditions (i.e. whether open or closed) in the network, particularly for events (e.g. major earthquakes or volcanic eruptions) where the effects are likely to be geographically wide-spread. It was therefore necessary to allow for the simultaneous closing of the Desert Road and the nearby alternative north-south route (State Highway 4) and connecting routes (Figure 4). There are three more distant alternative north-south routes, which were included in the network used for estimating the cost of link closures (Figure 4), but the probability that they will also be closed was deemed negligible. A total of 22 closure scenarios (i.e. combinations of the Desert Road with zero or more of the nearby alternative roads being closed) were considered.

In addition to considering the dependence of route conditions, it was necessary to consider the interactions between the different hazards (i.e. whether the occurrence of one hazard affects the occurrence of another hazard). Interactions can be ‘two-way’ or ‘one-way’ (e.g. snow and ice may increase the probability of a traffic accident occurring, but a traffic accident will have no effect on the probability of snow and ice forming). They can affect probabilities and/or consequences (e.g. snow or ice may have no effect on the probability of a volcanic eruption, but may make a lahar larger and more destructive).

The SATURN computer model was used to estimate traffic flows within the network, which included all towns in the region and roads used for travel through the region and/or between the towns in the region. All the roads are two-lane two-way highways, carrying between 500 and 5000 vehicles/day (i.e. the network is not congested). A user-optimal equilibrium traffic assignment was used, with the route choice depending on the time and distance costs, while the total cost of road closures was assumed to be the sum of:

- the change in the vehicle operating and occupant time cost;
- the lost user benefit from those trips that are cancelled or suppressed;
- the change in the accident cost (based on accidents being proportional to the vehicle-km of travel on each link).

When some links in the network are closed, trips using those links have to be redistributed to other routes, and the costs on the new routes will exceed the costs on the original routes, provided there is no change in the numbers of trips between the zones. As the price of making a trip increases, however, some travellers may well find that the new cost of travel exceeds the utility derived from making the trip, and will cancel their trip. This was modelled using the elastic assignment procedure available in SATURN, with the number of trips being related to the cost according to the power relationship:

$$T_{Cij} = T_{Oij}(C_{Oij} / C_{Cij})^P$$

where T_{Cij} and C_{Cij} are the number of trips and the travel cost (respectively) between an origin zone i and a destination zone j when one or more road links are closed, T_{Oij} and C_{Oij} are the corresponding number of trips and travel cost when all links are open, and P is the elasticity parameter. Now C_{Cij} will be greater than C_{Oij} for an uncongested network, and hence T_{Cij} will be less than T_{Oij} provided P is greater than zero. A good agreement between the predicted link flows with the Desert Road closed and the link flows observed during a nine-day closure (before the study commenced) was found for P equal to three.

Table 1 shows the total closure cost (per hour), along with the cost components, for four of the 22 closure scenarios, with elastic travel demand (P=3). All costs are expressed in July 1997 NZ$ (equivalent to US$0.66 in July 1997). While closure of the Desert Road alone costs the New Zealand economy nearly $8,000 per hour, closure costs reach nearly $23,000 per hour when the nearby major north-south route (State Highway 4) is also closed, and the detour lengths and the loss of user benefits (due to the suppression of travel) are greater. Simultaneous closures of other nearby roads have less impact, as they do not create a major barrier to the north-south traffic flow.

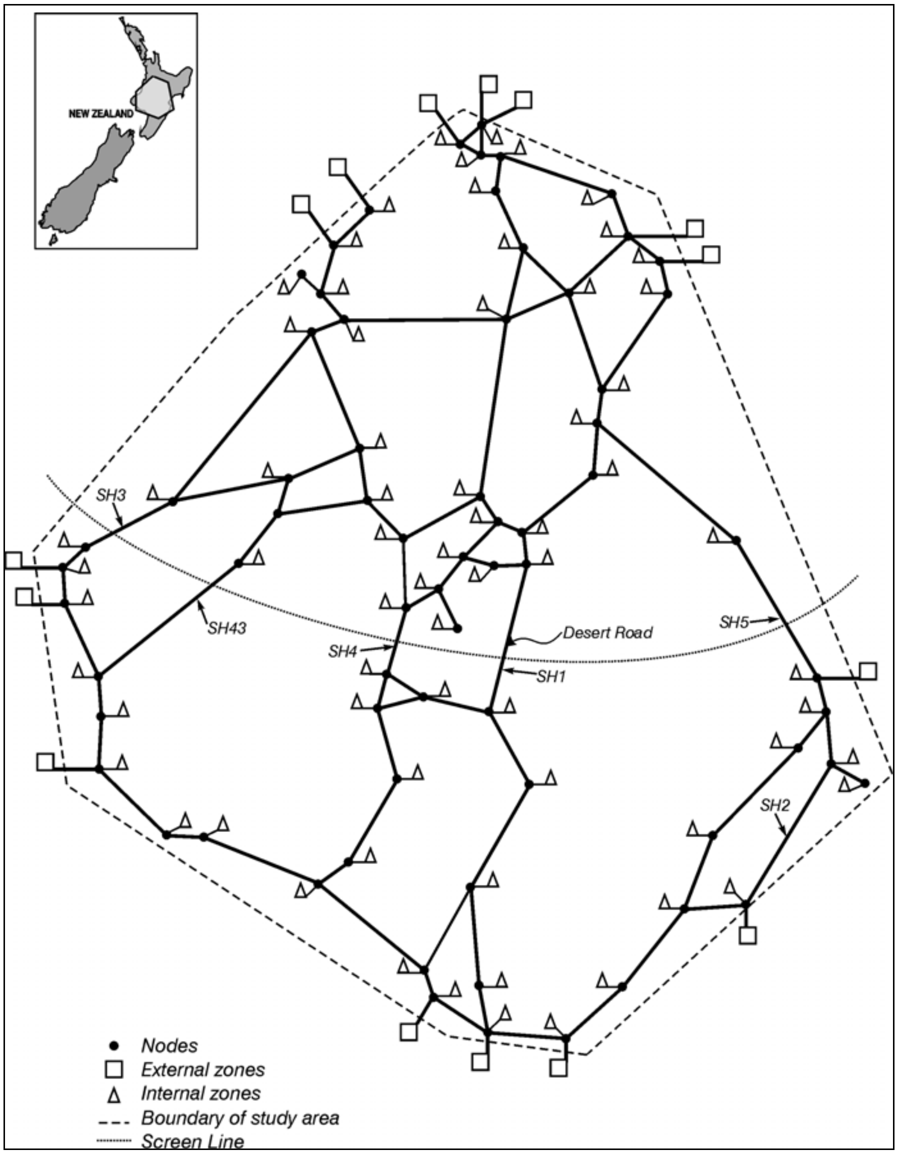

Figure 4: Network Model

Table 1: The Costs ($/hr) of Various Road Closure Scenarios

Closure Scenario	Operating plus Time	Accidents	Lost User Benefit	Total Cost	Total Cost of Closure
All Roads Open	180,590	43,017	N/A	223,607	N/A
Desert Rd Closed	172,610	40,858	18,129	231,597	7,990
Desert Rd and SH 4 Closed	164,412	38,570	43,498	246,480	22,870
Desert Rd and SH 47 Closed	165,220	38,846	33,887	237,953	14,350
Desert Rd and SH 49 Closed	169,944	39,783	26,058	235,785	12,180

It can be seen from Table 1 that the sum of the operating, time and accidents costs is less for the four closure scenarios than for the situation of all roads open, and this is also the case for the other 18 closure scenarios

[Dalziell, 1998]. It is important to note that it is only after the lost travel benefits, due to trips being cancelled or postponed, have been taken into account that one gets an economic loss due to road closure.

Table 2 shows the effect of closure of the Desert Road on travel within the whole network. If the elasticity of demand is ignored (i.e. *P*=0 and there is no change in the number of trips), the total travel and total cost are both predicted to increase (by about 2.2% and 2.6% respectively). These increases arise from the extra travel distance required to reach destinations. However, if the elasticity of demand is taken into account (i.e. *P*=3), the number of trips is predicted to decrease by 3.3%, with the consequence being that both the total travel and the total cost are both predicted to decrease (by 4.5% and 4.4% respectively).

Table 2: The Effect of Closure on Travel Within the Study Network

Measure of Effect	Desert Rd Open	Desert Rd Closed (*P*=0)	Desert Rd Closed (*P*=3)
Total Trips (veh-trips/h)	1,956	1,956	1891
Total Travel (veh-km/h)	299,890	306,610	286,250
Total Cost (veh-$/h)	180,590	185,210	172,610

Table 3 shows that closure of the Desert Road causes a 7.4% decrease in travel across the screenline (Figure 4), when allowing for the elasticity of demand. This is a larger reduction than for trips in the whole network, reflecting the fact that many trips do not involve using the Desert Road. It can also be seen that 80-90% of the traffic diverting from the Desert Road diverts to State Highway 4 if it is open, rather than the more distant alternative routes.

Table 3: The Effect of Closure on Flows (veh/h) Across the Screenline

Crossing Point	Desert Rd Open	Desert Rd Closed (*P*=0)	Desert Rd Closed (*P*=3)
SH1 (Desert Rd)	155	0	0
SH4	100	225	185
Other Routes	555	585	565
Total	810	810	750

The value of *P* indicates a high demand elasticity. This probably reflects the public perception that if the Desert Road is closed due to snow and ice, then the driving conditions on the nearby alternative routes will also be very dangerous, and the weather will be unsuitable for many recreational pursuits (the Central North Island is a popular recreation area), so fewer trips will be generated.

A point-estimate of the closure cost does not reflect the uncertainty regarding the probabilities and consequences of the hazards, and a standard risk evaluation method (Monte Carlo simulation) was used to obtain the probability distribution of the annual cost of closures for each hazard (Figure 5). This shows that snow and ice is the most important hazard, the expected annual cost being $1.9 million, compared to $1.5, $0.3 and $0.2 million for earthquakes, traffic accidents and volcanic events, respectively. In addition, the likelihood of the annual closure cost exceeding $1.2 million is much greater for closure due to snow and ice than for closure due to earthquake (or the other causes of closure).

The acceptability of the risks was then assessed, the criterion being that a risk is not acceptable if the benefit of mitigation (i.e. the reduction in the expected cost of road closure) is sufficiently greater than the cost of mitigating that risk (in New Zealand, the benefit/cost ratio must exceed about four). Mitigation options may affect the probability and/or cost of road closure. For instance, the threshold event size required for road closure may increase, and/or the time to repair and re-open the road may reduce. It was necessary to re-calculate the risk of road closure (by re-calculating the probability and cost of closure) with each mitigation option in place. The benefit of a mitigation option is the expected cost of road closure without the mitigation in place, minus the expected cost of road closure with the mitigation in place. This was compared to the sum of the capital and maintenance costs of the mitigation, to assess the worth of the mitigation.

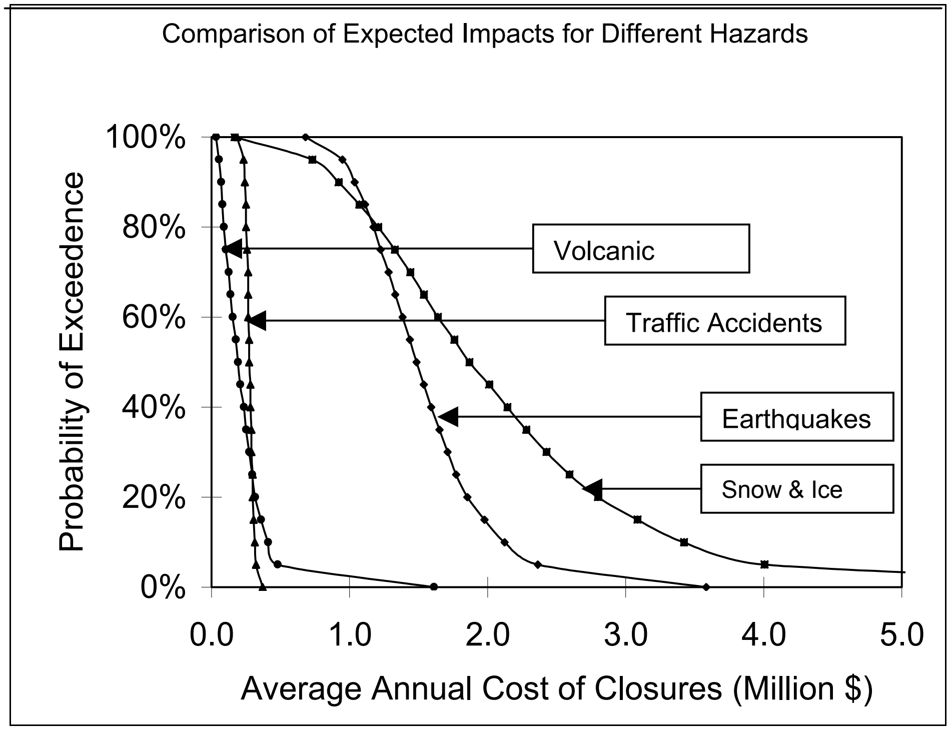

Figure 5: Closure Cost Exceedance Probabilities for Each Hazard

Four options for mitigating the effect of snow and ice were considered, namely the application of salt or calcium magnesium acetate (CMA), with and without a road weather information system (RWIS). The probability distribution of the benefit-cost ratio for each mitigation option was estimated (using Monte Carlo simulation). From this information, the likelihood that the benefit-cost ratio will exceed the threshold value for implementation was identified for each mitigation option.

It was found that the use of a RWIS, in conjunction with applying salt or CMA, enhances the benefit-cost ratio substantially, because it lowers the probability of road closure with a lower rate of application of salt or CMA. Although the 'salt with RWIS' option was the most attractive from an economics viewpoint, followed by the 'salt', 'CMA with RWIS" and 'CMA' options respectively, it was decided to apply CMA and investigate installation of a RWIS, because the adverse ecological effects of using salt within a National Park were deemed unacceptable.

National State Highway Network Study

Since the completion of the Central North Island study, research to:

- assess the feasibility of an all-hazards risk assessment for the whole State Highway network;
- develop a framework that captures the complexities of the task, while being cost-effective and practicable;

has been undertaken by Dalziell and Metcalfe [2004]. They concluded that a lack of statistical independence between the states of different parts of a networked system (i.e. one part being more likely to be damaged if another part is damaged), which was identified as a potential problem by Du and Nicholson [1997], is a major challenge, and using individual site hazard distributions can give misleading results. They also noted that there has been a move towards the use of scenario analysis to estimate system-wide losses for geographically distributed networks. The benefit of this is the greater ease of visualizing and communicating the potential losses to decision-makers, but it can be difficult to determine which scenarios should be included in the analysis. To resolve this issue, they propose using a "walkthrough scenario" approach [Taylor et al., 2001]. This involves randomly generating hazard events over an analysis period selected by the user, with a random process being used to generate (using hazard occurrence models) the number, size and location of hazard events during the period. If the user is interested in a 50 year exposure period, then a 250,000 year walkthrough period will give 5000 samples of 50-year exposure periods, upon which to base his/her conclusion.

Dalziell and Metcalfe [2004] note that an advantage of the "walkthrough scenario" approach is that it is possible to obtain a sense of when an event occurs and what other events might occur at much the same time. This information can be combined with classical discounted cash flow analysis, to assess how long after implementation of a mitigation option it is likely to be before the benefits of the implementation are achieved. They also note a difficulty with the approach, namely the very large number of simulations required if applying the approach to a large network where several different hazards exist. While the Central North Island Network study considered five hazard types (snow and ice, volcanic ash, lahar, earthquake and motor vehicle accidents), Dalziell and Metcalfe suggest a study of the National Highway Network would also need to include landslides, flooding, tsunami and wildfire. The computing requirement might be ameliorated using a form of artificial intelligence, where multi-criteria associative memory is used to identify similarities between scenarios [Chang et al., 2000]. If a scenario is generated that indicates a similar pattern of road closures to that indicated in a previously generated scenario, then the traffic modelling results for the previous scenario may be used rather than going through the full traffic modelling process again.

The Central North Island Network study included only the more tangible (or readily quantified) costs and benefits of closure and mitigation. Dalziell and Metcalfe note that a more holistic closure impact assessment is appropriate, with effects like community isolation being considered. They suggest that doing so would not be easy, because while the public might accept a short period of isolation, they may rapidly become less accepting as the period of isolation gets longer (reflecting the non-linear response of the public), especially if they perceive mismanagement of the recovery process, or if the recovery of the road network is slow compared with other critical infrastructure. The effect of road closure might depend heavily upon when it occurs (e.g. the impact on primary producers will be greater if the closure coincides with the harvesting period, than if it occurs at another time). The indirect economic impacts of closure may be very large; for example, Chang [2000] found marked long-term differences in the economic recovery of urban areas in Japan that suffered significant long-term traffic disruption after the Kobe earthquake, compared with those areas that had their transportation system restored soon after the earthquake.

URBAN ROAD NETWORKS

For the rural highway network studies described above, the level of congestion is such that demand variations can generally be readily handled, and supply variations are the major concern. Where the supply variation is due to a natural hazard event, closure duration is long and the use of equilibrium-based traffic modelling methods is likely to produce reasonably accurate of the effects on traffic flows a network. For urban road networks, which are typically dense and congested, both supply and demand variations are causes of major concern. Such variations in urban areas are typically of relatively short duration, and the appropriateness of equilibrium-based traffic modelling methods is extremely doubtful, because the time for moving towards equilibrium might be too short for reaching equilibrium (even approximately). An alternative approach is to use of microsimulation, where each individual vehicle is modelled for its entire trip through the road network, with its progress being determined by vehicle following, gap acceptance and lane changing models, plus the constraints formed by the physical properties of the road network (i.e. lane arrangement, traffic signal timings, etc.).

Berdica et al. [2001] used the Paramics computer model was used to study the effect of short-term closures in part of the road network in Christchurch, New Zealand (Figure 6). With this approach, Individual driver characteristics, including the level of aggression (used for determining the critical gap for lane changing) and the level of awareness (used for determining whether a driver will divert to minor roads to avoid congestion), can be considered. This model allows for drivers being presented with up-to-date information on the level of congestion in the network, and changing their route to avoid congestion (i.e. a dynamic assignment approach).

Closures of a road, located in the centre of the network and carrying much of the traffic to, from and through the area, were simulated. The closures ranged from 10 to 40 minutes, and were set symmetrically around the middle of the 8-9 am peak hour (i.e. the 20 minute closure started at 8:20 am and ended at 8.40am), with the simulation running beyond 9 am, to allow for the effects of closure to dissipate. Given the stochastic nature of Paramics, it was necessary to do multiple runs with different seed values for the randomisation processes, and the results presented here are the averages of five runs.

The study showed that the average travel time for a trip during normal operation (i.e. without any closure) is around 3 min. The average travel time increases only slightly for a closure duration of 10 minutes, but increases rapidly for longer closures, reaching almost 19 minutes for a 40 minute closure (Figure 7). The average travel distance is about 1.68 km during normal operation, and increases steadily to reach a maximum of 1.83 km for a 30 minute closure. It is interesting that for a longer closure, the average travel distance appears to decline. This is probably due to the network size, which did not allow drivers to divert a long way to avoid congestion. If the area surrounding the modelled network is congested, there will be little scope for reducing travel time by diverting, so the decline in average travel distance (as the closure duration gets quite long) might well occur for a larger network. It can be seen that the average travel time is much more sensitive to an increase in closure duration than is the average travel distance. This is not surprising, given the constraint upon the ability to divert.

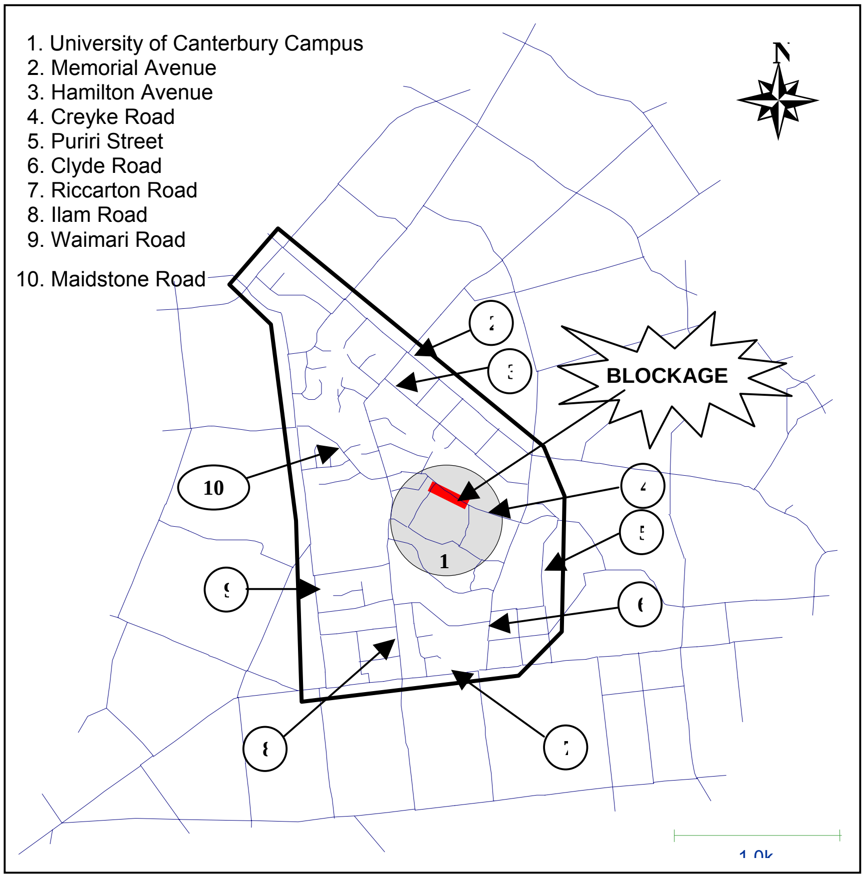

Figure 6: Coded road network: simulation network within the marked polygon

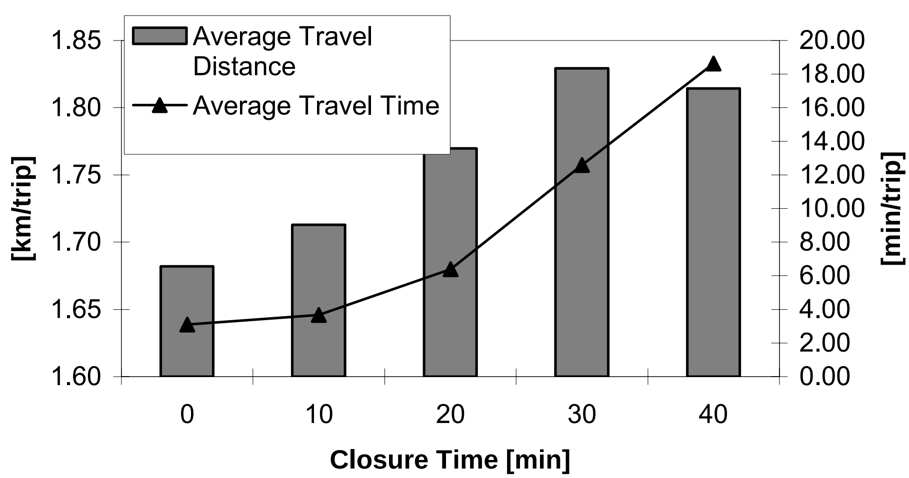

Figure 7: Average travel times and distances for different closures durations

Figure 8 shows how the average travel time varies as the starting time for trips changes. It can be seen that trips released well before the closure starts are not affected. The greatest effect on average travel time is for those trips which start at or shortly after the middle of the closure period (i.e. 8.30 am), and increases to about 27 minutes (or about six times the average travel time under normal operation) for a 40 minute closure. That is, the travel time is quite sensitive to variations in the trip starting time. It can also be seen from Figure 8 that as the closure duration increases, the travel time takes longer to return to the 'normal operation' value (i.e. 3 minutes), so that trips commenced well after the closure ends will experience greatly increased travel times.

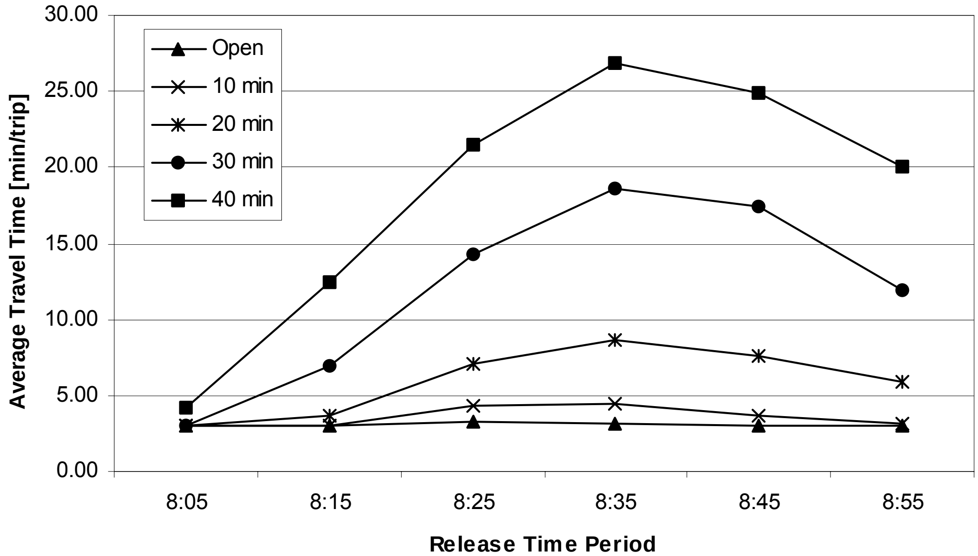

Figure 8: Average travel times for different closures durations

Berdica et al. [2001] also assessed the effect of closure duration on the travel cost (user time plus vehicle operating cost) within the study network, for trips to, from and through the area during the morning peak period (Table 4). Given that several short closures are likely within a city each day, the expected annual cost of them is likely to be larger than for occasional long closures in the inter-urban highway network.

Table 4: Travel Cost for Various Closure Durations

Closure Duration (min)	0	10	20	30	40
Travel Cost (July 1999 NZ$)	9,100	10,800	18,600	36,900	54,500

VALUATION OF TRAVEL RELIABILITY IMPROVEMENT

The standard transportation project appraisal procedure in New Zealand [Transfund NZ, 2004] provides for changes in the reliability of journey times to be included in the appraisal. The procedure allows for "the unpredictable variations in journey times, which are experienced for a journey undertaken at broadly the same time every day" (i.e. "day-to-day variations in traffic congestion, typically as a result of day-to-day variations in flow"). That is, the procedure allows for reliability associated with demand variations only, and "does not account for the delays that may result from major incidents on the road network" (i.e. incidents involving supply variations).

It should also be noted that the procedure does not estimate variations in the travel times of individual travellers, but estimates the variation in the mean travel times. The latter can be substantially less than the former, especially for periods with low flow rates, when there can be considerable variability in the travel times of individual travellers, because of the lack of constraint on their speed choice arising from traffic congestion.

The procedure involves using the standard deviation of travel time (s) as the measure of travel time variability. It is assumed that the standard deviation of travel time it is related to the ratio of the volume (v) to the capacity (c) according to the following sigmoid-shaped relationship:

$$s = s_{min} + \frac{(s_{max} - s_{min})}{1 + exp[b(\frac{v}{c}) - a]}$$

where s_{min} and s_{max} are the minimum and maximum standard deviations of travel time (when v equals zero and c respectively), and a and b are constants. The values of s_{min}, s_{max}, a and b vary according to the type of facility (e.g. motorway, urban arterial, rural highway, signalised intersection, unsignalised intersection).

It can be shown that the above relationship for the standard deviation of the travel time implies that the standard deviation:

- equals s_{min} when v equals zero;
- increases only gradually as v increases from zero to about 0.85ac;
- increases rapidly as v increases from about 0.85ac to about 1.15ac;
- equals [(s_{min} + s_{max})/2] when v equals ac;
- increases gradually towards s_{max} as v increases above about 1.15ac.

The use of the standard deviation of travelling time as the measure of variability has the advantage that the units are the same as the units of travelling time, and the appraisal procedure values a one minute reduction in the standard deviation of travel time at 0.8 and 1.3 times the value of a one minute reduction in the travel time, for cars and commercial vehicles respectively. The procedure involves assessing the change in the standard deviation of travel time for only a part of most journeys (i.e. the part of the journey on the part of the network which might be changed).

Whereas the travel time for a journey is simply the sum of the travel times for the segments of the journey, and the variance of the travel time for a journey is simply the sum of the variances of the travel times for the segments of the journey, the standard deviation of the travel time for the complete journey (s_{total}) is not the sum of the standard deviations of travel times for the n (say) segments, as:

$$s_{total} = \sqrt{(s_1)^2 + (s_2)^2 + ... + (s_n)^2} \neq s_1 + s_2 + ... + s_n$$

Hence, one cannot place a value on a reduction in the standard deviation of the travel time for one segment of a journey, without knowledge of the variability of travel times for the other segments.

In reality, transportation system users are interested in the variability of the travel times for complete journeys. Now

$$\sqrt{(s_1)^2 + (s_2)^2 + ... + (s_n)^2} < s_1 + s_2 + ... + s_n$$

and the discrepancy increases as the number (n) of segments with unpredictable travel time increases. Hence an x% reduction in the standard deviation for one segment will mean a smaller than x% reduction in the standard deviation for the complete journey (i.e. the change in journey travel time reliability will be over-estimated), and the degree of over-estimation will increase as n increases. The economic appraisal procedure [Transfund NZ, 2004] allows for this, by multiplying the value of a reduction in the standard deviation of travel time for part of the trip by a factor, which varies from 100% for regional models to 50% for corridor models to 30% for intersections and individual passing lanes.

TRANSPORT NETWORK RESILIENCE

Definitions

In addition to promoting the four-phase approach (i.e. reduction, readiness, response and recovery), the recent upsurge of attention to Civil Defence and Emergency Management (CDEM) in NZ has resulted in greater attention being given to the concept of 'resilience'. This refers to the ability of a system to accommodate variable and unexpected conditions without there being a catastrophic failure, and has been defined as "the capacity to absorb shocks gracefully" [Foster, 1993].

It is helpful to distinguish between a 'crisis' and a 'disaster'. A crisis occurs when there is an event which has the potential to lead to a disaster, while a disaster occurs when a system is pushed beyond a state of relative stability or equilibrium, and its capacity to manage or control the situation is overwhelmed. That is, a crisis precedes a disaster, but is not necessarily followed by a disaster. The term 'vulnerability' refers to the ease with which the system can be pushed outside its state of stability or equilibrium. Resilience refers to the ability of a system to respond to a crisis situation and prevent it escalating into a disaster or, if this is impossible, the ability of the system to withstand the stresses imposed by the disaster and to function in the changed environment.

Given the importance of business interruption losses, which can far exceed property losses [Münchener Rück, 2001] the ability of business and other organisations to respond and recover is getting more attention. A six-year research programme has recently commenced at the University of Canterbury, with the aim of minimizing the business interruption losses associated with crises and disasters. This research has three 'objectives' or parts, as described below.

Organisational Planning for Hazard Events

The goal of this 'objective' is to understand how New Zealand organisations prioritise investment for hazard events, develop a framework for improved internal organisational planning, and facilitate integration of hazard planning with other organisations. A case study approach is being used, with the selected organisations including the State Highway Authority, a major roading contractor, a rural District Council, and various private businesses.

This 'objective' will explore the following issues:

- how organisations dedicate resources to prepare for and respond to hazards, the reasons for investment in emergency planning and how obligations to customers, regulators, government policy, and accounting practices influence these;
- the use of risk management approaches to emergency planning and how very low probability, extreme consequence events and the potential for organisational collapse are managed;
- the sophistication of operational and strategic plans for responding to extreme events, critical interfaces between organisations and how these are addressed;
- the consultation and communication of risk and expectations within organisations, with their stakeholders, between organisations and with the community.

Prioritisation and Deployment of Physical and Human Resources

The goal of this 'objective' is to develop a decision support tool that can be used following a hazard event for prioritising physical response and recovery of networked infrastructure, as the prioritisation of repairs across damaged networks is an issue for many lifeline providers. The road network has been chosen as the case study because of its importance as a key lifeline in the aftermath of a hazard event.

This 'objective' will focus on the following issues:

- how information is collected and communicated during response and recovery activities at present, and which aspects of this process are effective or less effective;
- what the information requirements of different stakeholders are during response and recovery activities, and how data collection activities and analysis can be prioritised to meet these requirements;
- how information and decision-making are shared between organisations, particularly where critical links cross organisational boundaries (such as State Highways interfacing with major urban arterials), and how the process might be better facilitated in the future;
- to scope and develop a decision-support tool for road managers that help them to assimilate actual damage information as it is received and to optimise the deployment of available resources and prioritise infrastructure repairs.

Legal and Contractual Frameworks

The goal of this 'objective' is to establish a comprehensive procurement framework and programme management plan for reconstruction in the event of a national natural disaster. It is unlikely that current normal procurement mechanisms used in the construction industry will deliver the best economic outcome in the event of a national disaster. It is likely that without a comprehensive reconstruction procurement framework, rapid reconstruction will be significantly hampered.

This 'objective' will focus on the following issues:

- the analysis of subcontracting arrangements and how will they be affected after a major disaster, the interconnectedness between organisations where they use common contractors, and the impact this may have on recovery;

- the analysis of NZ legal frameworks for construction (specifically the Resource Management Act and the Building Act), the relevance of these Acts to post-disaster reconstruction, whether they would help or hinder, and whether the current Acts can be used to develop a legal framework for reconstruction;
- the analysis of contractual aspects of construction projects (especially common construction contracts used in NZ) and their relevance and usefulness after a natural disaster, and the analysis of international contracts and how these standard contracts can be/have been modified to suit New Zealand conditions;
- the analysis of major international disasters and contracts for rebuilding, how contracts to rebuild after a disaster have been set up, the procurement mechanisms that have been used and the applicability of this international experience in New Zealand.

CONCLUSION

The assessment and management of risk associated with natural hazards has been receiving considerable attention in New Zealand for some time. The focus was initially on reducing the risk through infrastructure improvements, especially the strengthening or replacement of those transport network components (especially bridges) that were considered weak and likely to fail, as a result of hazard events that are rare but may have dramatic consequences (e.g. earthquakes and volcanic events).

The Central North Island study has highlighted the fact that as far as user costs are concerned, the impact of more frequent events with less dramatic consequences (e.g. road closures due to snow and ice during storms) may exceed the impact of rare events with more dramatic consequences. In addition, it has highlighted the need to consider the whole network, and allow for the re-routing of traffic, especially where the re-routing leads to such increases in user costs that the travel demand is reduced substantially. In such circumstances, the loss of benefit associated with trips being cancelled or postponed needs to be taken into account.

The Central North Island study has resulted in recognition of the likely benefits of undertaking a risk assessment and management a study for the national State Highway network. While such a study has not yet been done, it seems likely that a ‘walk-through scenario” approach would be the best way to proceed, if the important matter of the dependency of network component states is to be addressed properly.

There is rapidly growing concern about the reliability of travel within urban networks, especially where there is considerable traffic congestion. The study of one urban network has revealed that the impact of short closures on user costs can be quite substantial, and given the frequency of such closures, it is likely that the impact will be at least as great as for long closures resulting from natural hazard events. Equilibrium-based models, while appropriate for long closures, are not appropriate for short closures, for which a microsimulation approach seems suitable.

It has recently been decided to use the standard deviation of travel time as the measure of travel time reliability, for including the benefits of improvements in travel time reliability in the appraisal of urban transport network projects. There is a methodological problem associated with this approach, arising from the need to estimate the effect of a reduction in travel time variability for part of a trip, on the variability of the travel time for the complete trip.

The concept of transport network resilience appears to hold considerable promise. It appears that the concept can be applied to organisations which are users of the transport system, as well as those responsible for the proper functioning of the system (the road controlling authorities). While road controlling authorities might seek to reduce unreliability arising from supply variations, users might seek to adjust their business arrangements so as to reduce the effect of supply variations on their organisation. This might lead to changes in the pattern of transport demand and hence the nature and extent of demand variations.

Finally, given the increasing use of “just-in-time” production methods, it is likely that transport network reliability will continue to increase in importance. There is a wide range of threats to the reliability of urban and rural networks, and a range of analysis methods are required to assess the effects on network reliability. Research into organizations using road networks and what they can do to increase their resilience, by changing the way they operate, will complement the research into how road controlling authorities can improve the reliability and resilience of road networks for users, and is a welcome development.

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