AVALANCHE RISK EVALUTION WITH PRACTICAL SUGGESTIONS FOR RISK MINIMISATION: A CASE STUDY OF THE MILFORD ROAD, NEW ZEALAND

Jordy Hendrikx [a*] Ian Owens [b], Wayne Carran [c], Ann Carran [c]

[a] National Institute of Water & Atmospheric Research Ltd. (NIWA), Christchurch, New Zealand
[b] Department of Geography, University of Canterbury, Christchurch, New Zealand
[c] Works Infrastructure, Te Anau, New Zealand

ABSTRACT: This paper examines two methods for risk evaluation in a case study for the Milford Road, New Zealand. These results are then used to quantify the effect of the avalanche programme in reducing the risk and enable clear comparisons with other roads around the world. The Milford Road (State Highway 94) between Te Anau and Milford Sound, is the only public highway with a significant avalanche problem in New Zealand. Significant avalanching occurs on the Milford Road, because of the over-steepened, glacially carved terrain combined with very heavy precipitation that exceeds 8000 mm per year. Milford Sound, at the end of the Milford Road, has been recognized as a world heritage area, and is becoming an increasingly popular tourist destination. Over 400,000 people visit Milford Sound annually and the majority of these arrive by road. Furthermore, the daily traffic flow is strongly tidal, causing periods of very high traffic concentrations in the mornings and the evenings. The Transit New Zealand Milford Road Avalanche Programme has been responsible for managing the avalanche risk to these travelers, since its inception in 1983.

With continually increasing traffic flow and avalanche risk management, we examine the present avalanche risk, as described by the Avalanche Hazard Index (AHI) in common use in North America, and the Probability of Death to Individuals (PDI) method more commonly used in Europe. We also comment on the sensitivity of these methods to the various assumptions made in the analysis and quantify the effect of various control and management strategies on the avalanche risk. We conclude with some practical suggestions which have successfully been used to minimise the risk on the road.

KEYWORDS: Avalanche Risk, Hazard Index, Traffic, Milford Road, New Zealand.

1. INTRODUCTION

The Milford Road (State Highway-94) is located in the Fiordland region, which is in the southwest of the South Island of New Zealand (Figure 1). This region is characterised by a landscape formed during Pleistocene glaciation of resistant bedrock, that has resulted in U-shaped valleys with very steep sides and extensive occasionally permanent snowfields perched above (Owens and Fitzharris, 1985). Significant avalanching occurs in Fiordland because of the over-steepened terrain combined with very heavy precipitation that exceeds 8000 mm per year (Owens and Fitzharris, 1985). Winter storms often deposit in excess of 2m of snow in the start zones.

The Milford Road extends for 119km from Te Anau to Milford Sound (*Piopiotahi*) through Fiordland National Park which is part of Southwest New Zealand World Heritage Area (*Te Wāhipounamu*). The final 29km of the road before Milford Sound passes through a significant avalanche area. It is the only public highway with a significant avalanche problem in New Zealand. It has long been known that the Milford Road has as severe an avalanche problem as any other mountain highway in the world (LaChapelle, 1979; Conway et al., 2000). The Transit New Zealand Milford Road Avalanche Programme has managed the avalanche risk on the road since 1983. Over the years the avalanche programme has been under constant assessment, improvement, international peer review (Föhn, 1999), and research (Fitzharris and Owens, 1984; Weir, 1998; Carran et al., 2000; Conway et al.,2000, 2002; Hendrikx et al., 2004, 2005). A testament to the success of the Transit New Zealand Milford Road

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Corresponding author address: Jordy Hendrikx,
National Institute of Water & Atmospheric Research Ltd.
(NIWA), Christchurch, New Zealand;
Phone: +64 3 348 8987 ext. 3771; Fax: +64 3 364 2907
E-mail: j.hendrikx@niwa.co.nz

Avalanche Programme is that since the avalanche programme officially, began there has been no loss of life.

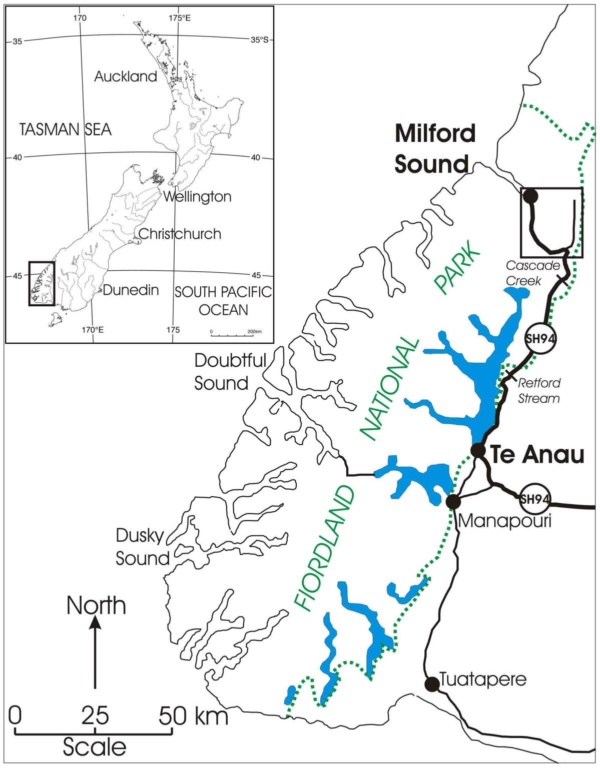

Figure 1: Location Map of the Milford Road (SH94) from Te Anau to Milford Sound and the Fiordland National Park. The avalanche area, is shown by the rectangle north of Cascade Creek and south of Milford Sound

1.1. Tourism and traffic

Fiordland National Park is part of the Southwest New Zealand World Heritage Area (*Te Wāhipounamu*) It is one of approximately 400 outstanding natural and cultural sites world wide which have been recognised by UNESCO (Department of Conservation, 2002). In recent years Fiordland National Park has experienced a steady increase in visitor numbers and growth in both domestic and international tourism is forecast to continue (Department of Conservation, 2002).

Tourism is now considered vital to New Zealand's economy, directly and indirectly contributing almost 10% of New Zealand's GDP and supporting one in ten jobs (Ministry of Tourism, 2005). Tourism is also very significant for the local and regional economy of Te Anau and Fiordland. Closure of the Milford Road disrupts tourist traffic and fishermen from Milford Sound, and has very serious financial implications for businesses in Milford and in Te Anau. In 1980, closure of the Milford Road was estimated to have cost $750,000 in lost revenue alone (Dingwall et al., 1989). Furthermore, an incident involving one or more tourist buses on the Milford Road has the potential to do severe medium term damage to New Zealand's tourism industry (Weir, 1998).

1.2 Increased vehicle numbers

Some of the most striking features of the Southwest New Zealand World Heritage Area are revealed along the Milford Road and in Milford Sound, the end point of the Milford road. According to the Department of Conservation(2002) approximately 75% of road users are international visitors and the vast majority of visitors, almost 90%, travel the full length of the road from Te Anau to Milford Sound. The main reasons people use the road is to undertake a scenic cruise on Milford Sound, which is an internationally recognised icon tourist destination. In 2002, more than 410,000 people visited Milford Sound, up from 247,000 in 1992 (Department of Conservation, 2002). Transit New Zealand(2002) conducts traffic counts along the Milford Road (Figure 2), but it has been noted that there are some discrepancies in their data (URS, 2004). Foremost among these discrepancies is that the volume at Falls Creek (near to Cascade Creek site in Figure 1) is on an annual basis consistently much greater than at the Retford Stream site (Figure 1), which is closer to Te Anau. The reverse trend in traffic volumes would be expected. Despite these concerns in the Average Annual Daily Traffic (AADT) data for the Milford Road, all available data does indicate a strong and consistent growth rate. When a forecasted AADT is calculated for the period 1975 to 2005 using a combination of Falls Creek and Cascade Creek data a growth rate of 3.2% is calculated (Figure 2).

Of more concern to an avalanche programme is the winter traffic volume, rather than the AADT. URS(2004) calculated a Winter Average Annual Daily Traffic (WAADT) of 381 for 2003, where the winter avalanche period was defined as mid June to mid December. If we assume that WAADT follows the same growth rate as the AADT, the 2005 WAADT can be estimated at 406.

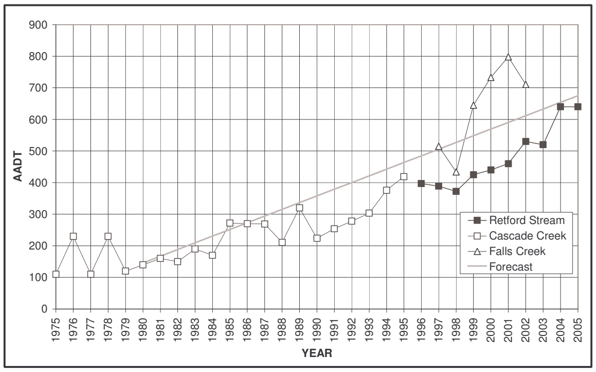

Figure 2: Transit New Zealand AADT for Retford Stream, Cascade Creek and Falls Creek sites on the Milford Road for the period 1975 to 2005. Forecasted AADT is calculated for the period 1975 to 2005 using a combination of Falls and Cascade Creek data, and shows a growth rate of 3.2%.

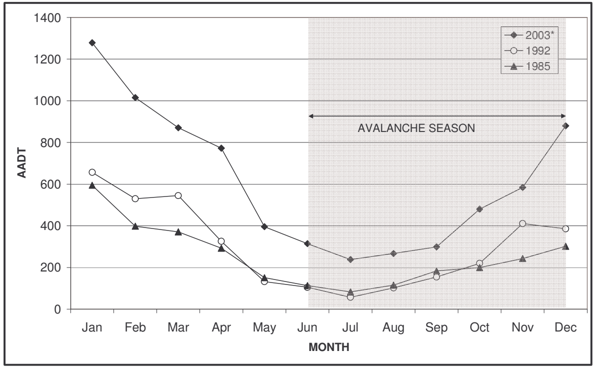

Figure 3: Monthly trends in Transit New Zealand AMDT at the Cascade Creek site on the Milford Road, clearly showing the increased use of the shoulder seasons. Of greatest concern is the spring shoulder season, at the end of the avalanche season. *2003 data from Retford Stream site.

1.3 Changes in seasonal distribution of vehicle numbers

The estimation of the WAADT also took into account the seasonal distribution of travellers to Fiordland National Park. The main visitor season for Fiordland National Park occurs from mid October until the end of April, peaking between January and March. The Department of Conservation(2002) has noted a moderate increase in visitation to the major attractions of Fiordland National Park outside of the traditional visitor season, and have realised that the prominence of these shoulder periods may have implications for future visitor management. When examining the Transit New Zealand Average Monthly Daily Traffic (AMDT) values for several years (where available) there is a clear increase in the volumes during the shoulder seasons (Figure 3). Of great concern from an avalanche safety viewpoint, is the increase in the AMDT from October onwards, as this often coincides with maximum snow accumulation, large rain on snow events, and the occurrence of the large climax type avalanches. Of further concern is the draft management plan for Fiordland National Park (Department of Conservation, 2002) in which there is a suggested recommendation to set a limit of 4000 visitors per day to Milford Sound. If this limit were implemented it would increase and extend the high AMDT values further into the shoulder seasons.

1.4 Changes in vehicle types

Travers Morgan(1995) noted that the effect of completing the sealing of the road in 1995 has caused a shift in independent travellers from using buses to cars. This has resulted in changing the types of vehicles on the road, as well as the total number. However, in 2003 there was still approximately 14% of the total traffic as buses, with over 100 buses per day during summer (URS, 2004). With the proposed alternative forms of transport from Queenstown, including the development of a gondola or monorail to the lower Hollyford Valley, this could see the proportion of buses in the avalanche area significantly increase in the future.

1.5 Daily distribution

Of concern from an avalanche safety and risk viewpoint, is that the daily traffic flow is strongly tidal, with traffic flow predominantly into Milford Sound in the morning and out in the afternoon. This results in periods of very high traffic concentrations in the mornings and the evenings. In the case of an incident, the resulting number of waiting vehicles endangered by avalanches would be significantly greater than the AADT would suggest. This has been shown to be an important contributor to avalanche risk (Schaerer, 1989).

2. AIMS

This paper aims to examine the application of two risk assessment methods, the Avalanche Hazard Index (AHI) and the Probability of Death to Individuals (PDI), to examine the present avalanche risk on the highway. This will be compared to the risk of a theoretical uncontrolled avalanche regime, as estimated by Fitzharris and Owens(1980), but with traffic at 2005 winter levels. The difference between the present controlled and theoretically uncontrolled regime will then be estimated to give a measure of the effectiveness of the Transit New Zealand Milford Road Avalanche Programme. The sensitivity of these methods to the various assumptions made in the analysis are examined leading to practical suggestions for risk minimisation. Finally, the level of risk on the Milford Road is compared to other roads in Switzerland in terms of collective risk and with Rogers Pass, B.C., Canada in terms of the AHI.

3. METHODS

3.1 Avalanche Hazard Index (AHI)

The AHI was first developed in 1974 for use on highways in British Colombia, Canada (Avalanche Task Force, 1974). It was designed as a numerical expression of damage and loss as a result of the interaction between vehicles on a road and a snow avalanches (Schaerer, 1989). Since then it has been used on other roads, elsewhere in Canada (e.g. Schaerer, 1989; Stethem et al., 1995), the United States of America (e.g. Armstrong, 1981) and on the Milford Road, New Zealand (Fitzharris and Owens, 1980). The AHI is used to determine how serious avalanche problems are, to allow comparisons of the hazard of different highways, to establish priorities and determine the appropriate level of avalanche safety management and to show where control measures have the greatest effect (Schaerer, 1989). The AHI considers both moving and waiting traffic, and is a function of: the size and type of avalanche, the frequency of avalanche occurrences, the number of avalanche paths and the distance between them, the total length of highway exposed, the traffic volume, the traffic speed and the type of vehicle.

Fitzharris and Owens(1980) undertook an assessment of the AHI on the Milford Road, by estimating the frequency and size of avalanches from historical information (e.g. Smith, 1947), local knowledge (e.g. Andrews pers. comm., 1979 [In] Fitzharris and Owens, 1980) as well as topographical and botanical field investigations. Estimates were made for the size and frequency of the three different types of avalanches, powder snow (k_1), light snow (k_2) and deep snow (k_3). Smith(1947) found that because of the very steep terrain certain snow conditions result in airborne avalanches. Therefore Fitzharris and Owens(1980) introduced an additional avalanche type, plunging avalanches (k_4). These different avalanche types have weightings that consider the relative cost and consequence of an encounter, where k_1=1, k_2=4, k_3=10 and k_4=12. Using these weightings, and the different frequencies and avalanche widths associated with each, Fitzharris and Owens(1980) calculated the AHI for the Milford Road using the encounter probability for moving and waiting traffic according to the following equation:

$$AHI = \sum_{k=1}^{4} W_k (P_m + P_w) \qquad (1)$$

where:
k = index for avalanche type k_1 to k_4
W = weighting for avalanche type
P_m = encounter probability for moving traffic
P_w = encounter probability for waiting traffic

The 1980 AHI on the Milford Road was calculated at 46 for a winter traffic volume of 80 vehicles per day, where P_m = 2 and P_w = 44. According to the North American practice to group highways with respect to the avalanche hazard (Avalanche Task Force, 1974) the Milford Road rated at a moderate hazard in 1980.

Schaerer(1989) modified the descriptions of the avalanche types and their weightings, which has resulted in any subsequent calculations of AHI to be about 0.7 to 0.9 times the indices calculated with the original weightings. Schaerer(1989) also standardised the method for calculating the AHI, provided some examples, and thereby made the process more repeatable. In doing so he restated the equations for moving traffic and waiting traffic.

The equation for waiting traffic now included a value to explain the probability of a subsequent avalanche on an adjacent path (P_s). These values range from 0.05 to 0.3 and have been determined from observations at Rogers Pass, Canada (Schaerer, 1989). Fitzharris and Owens(1980), with no information about how an avalanche occurrence would be related to another avalanche at an adjacent site used a value of 0.15 for P_s. Armstrong(1981) suggested a lower value of P_s at 0.03-0.05 for Red Mountain Pass in Colorado. Schaerer(1989) related the P_s value to the characteristics of the avalanche starting zones, noting that a high P_s value would be appropriate for avalanche paths with similar aspects and terrain characteristics.

Schaerer's(1989) equations also calculate the length of a queue of waiting traffic (L_w), based on average traffic volume. The safe waiting distance between each avalanche path, combined with the queue length, will determine how many vehicles are then exposed in an adjacent avalanche path, in both directions. However, in the analysis for this paper queues have not been calculated using the average daily traffic volume, but rather the peak volume as traffic flow is distinctly tidal. While using the June peak flow rate to determine the queue length for waiting traffic could lead to an overestimation at times, there are also times when this may in fact still be an underestimation e.g. the final two hours preceding road closure for avalanche hazard during the spring shoulder season.

Schaerer(1989) also considered the case of a second avalanche on a path which is already blocking the traffic (P'_s). Schaerer(1989) suggested that values for P'_s can range from 0 to 0.5 and must be chosen from a study of the terrain and for most avalanche paths with a single starting zone P'_s=0. In this analysis P'_s has been set at 0 as avalanches need to be substantial to reach the road, and will usually clear any instability in a given start zone.

The equations proposed by Schaerer(1989) have been used to calculate both the controlled and theoretically uncontrolled avalanche regime on the Milford Road for the present (2005) situation.

3.2 Probability of Death to an Individual (PDI)

The PDI is a method used to express risk. It has been widely used for hazard assessment for a range of natural (e.g. landslides) and anthropogenic (e.g. dams) hazards. Weir(1998) undertook an assessment of risk on the Milford Road using a PDI and Fatal Accident Rate (FAR) methods, where FAR is expressed as the probability of a fatality per 100 million person hours of exposure. Weir(1998) postulated that it might be reasonable to expect a fatal accident every 20 years ± 10 years, based on accounts of two near misses (while the road was closed), and the road maintenance contract being tendered every three years. This assumption was then used in combination with exposure time to calculate FAR. However, to date, there has only been one fatality on the Milford Road since 1983 (on a closed road), and while the contract has been re-tendered on a three to five year basis, the contract has remained with what is now called Works Infrastructure since the programs inception. The assumptions of Weir(1998) are somewhat subjective, poorly constrained and based on too many broad assumptions with limited numerical basis. Therefore, it was deemed necessary to re-evaluate the PDI of the Milford Road more rigorously using some more stringent controls on the variables used, and following a less subjective, more repeatable methodology.

There have been some recent attempts to standardise a method to express the risk in terms of a PDI for a road with an avalanche hazard (Wilhelm, 1998; Kristensen et al., 2003; Margreth et al., 2003; Norwegian Geotechnical Institute (NGI), 2003). This paper uses the methods described by Wilhelm(1998) and Margreth et al.(2003) as they are based on fewer assumptions, the variables considered are more clearly explained, they have a large data set of road traffic avalanche fatalities and they have also been applied to several pass roads in Switzerland.

According to Wilhelm(1998) and Margreth et al.(2003), the collective risk (expressed as deaths per year) on a road crossed by n avalanche paths is given by:

$$CR = \frac{T.\beta}{24}\sum_{i=1}^{n}\frac{L_i}{R_i.V}\lambda_i \qquad (2)$$

where:

CR = collective risk (deaths year^{-1})

T = average traffic volume for avalanche period (vehicles d^{-1})

β = mean number of passengers per vehicle (β_B = buses, β_C = cars)

n = number of avalanche paths

L_i = width of avalanche = average length of road covered by avalanche i (km)

R_i = return period for avalanche i (years)

V = speed in (kmh^{-1})

λ_i = probability of death in a vehicle hit by an avalanche

While the parameters, T, β, n, L_i, V and λ_i can be measured on site or determined from historical records, Margreth et al.(2003) estimate R_i from slope angle in the starting zones and track. Slope angle and return period has been plotted for the available avalanche information from four pass roads with the remaining paths having their R_i extrapolated based on this relationship.

The risk, or probability of death to an individual (PDI) can be calculated according to Wilhelm (1998) and Margreth et al.(2003) using:

$$IR = \frac{z}{24}\sum_{i=1}^{n}\frac{L_i}{R_i.V}\lambda_i \tag{3}$$

Where:

IR = individual probability of death (year^{-1})

z = number of passages per day of that person (i.e. commuter passengers z = 2, road crew z = 6)

The number of passages for the road crew depends on the condition of the road, and Wilhelm(1998) suggested that it be set at 6. For a daily commuter (e.g fishermen, bus drivers and helicopter pilots) the number of passes is 2. In Switzerland it has been found that on pass roads the mean number of passengers per vehicle β is normally 1.6 (Margreth et al., 2003). In the Swiss Alps between 1946 and 1999, 167 passengers were buried by avalanches in their vehicles, of whom 30 persons or 18% died. Therefore $\lambda_i = 0.18$ in equations (2) and (3). Kristensen et al.(2003), despite lacking data, suggested a higher death rate of 40% or 0.40 because of Norway's topographic characteristics, remoteness and long rescue time. Schaerer(1989) however, provided a range of probabilities of death depending on avalanche type, from 0.05 for light snow to 0.25 for deep snow avalanches. To better enumerate the PDI, the following improvements to the calculation to account for different avalanche types and resulting probabilities of death are suggested, for collective risk:

$$CR = \frac{T.\beta}{24}\sum_{i=1}^{n}\sum_{j=3}^{5}\frac{L_{ij}}{R_{ij}.V}\lambda_{ij} \tag{4}$$

and individual risk:

$$IR = \frac{z}{24}\sum_{i=1}^{n}\sum_{j=3}^{5}\frac{L_{ij}}{R_{ij}.V}\lambda_{ij} \tag{5}$$

where:

j = avalanche type j_3 to j_5

Margreth et al.(2003), while not specifying different avalanche types, use 0.18 as the probability of death for an avalanche that can bury a vehicle, which may be approximately equal to the deep snow avalanche type of Schaerer(1989). However, Schaerer(1989) has a higher probability of death for this avalanche type (j_4) at 0.25. In the absence of fatality data, plunging snow (j_5) has been set at a high probability of death of 0.50 because of the continued evidence of the destructive nature of these avalanches on the Milford Road. Light snow avalanches (j_3) were assigned a probability of death of 0.05 by Shearer(1989). As there is limited data available on the probability of death for each avalanche type, this study uses numbers on the upper limit for avalanche type j_3 (0.05) and j_4 (0.25) as suggested by Schaerer(1989). The ratio of cars to busses also needs to be considered as the number of people in each type of vehicle will differ, as too will the respective death rate. To account for this, a ratio of cars to busses *C:B* has been added.

Unfortunately, one significant component of the risk that the PDI method as described by Wilhelm(1998) and Margreth et al.(2003) does not consider, is that posed to waiting traffic. This is because of the extensive model assumptions needed to make these calculations (Margreth et al., 2003). Kristensen et al.(2003) and NGI(2003), have described a series of complex calculations which attempt to enumerate the increased risk for waiting traffic with increasing queues, while simultaneously decreasing the risk over time, as the probability of a second avalanche reduces. Unfortunately, the calculations were based on cumulative assumptions that were considered unrealistic for application on the Milford Road. An alternative method to calculate the PDI for waiting traffic including the effect of different avalanche types is an area of current ongoing research.

Waiting traffic has been shown to be extremely important in applications of the AHI (Fitzharris and Owens, 1980; Schaerer 1989). In the case of the Milford Road, waiting traffic contributed over 95% to the AHI (Fitzharris and Owens, 1980). Therefore, calculations of PDI using the Wilhelm(1998) and Margreth et al.(2003) method are likely to be lower than the actual PDI would be during periods involving waiting traffic. This makes the direct comparison of the PDI for avalanche risk difficult to compare with other hazards. However, the modified PDI method of Wilhelm(1998) and Margreth et al.(2003) does allow for easy comparisons between different roads, though this could be compromised if there were significant differences in the path configuration, e.g. single well spaced paths compared to clusters of paths.

The modified equations of Wilhelm(1998) and Margreth et al.(2003) have been used to calculate both the controlled and theoretically uncontrolled avalanche regime on the Milford Road for the present (2005) situation.

4. RESULTS & DISCUSSION

4.1 AHI Results

Using equation 1, and the weightings proposed by Schaerer(1989) the AHI of the controlled and theoretically uncontrolled avalanche regime on the Milford Road for the present (2005) situation has been calculated. Both of these analyses have been undertaken using the same input parameters:

T = 406 estimated average daily winter traffic volume in 2005.
V = 11 ms^{-1} (Fitzharris and Owens, 1980)
D = 20 m (Fitzharris and Owens, 1980)
L_v = 15 m (Fitzharris and Owens, 1980)
t = 2 h (Schaerer, 1989)
L_w = 525m (Calculated using L_v and a peak winter flow of 35 vehicles h^{-1})
P_s = 0.15 (Fitzharris and Owens, 1980)

Based on the database of all avalanche occurrences on an open road and using the above parameters, the current controlled avalanche regime was calculated to have a AHI of 2.80, comprised of a P_m of 0.61 and P_w of 2.19. This must be viewed as an absolute maximum, as in practice queues are never allowed to become as long as 525m, the average speed of traffic is often greater than 11 ms^{-1} (40 kmh^{-1}), and stopping distances are often shorter because of snow free roads. Furthermore, the current road operators are very aware of times of increasing hazard while the road is open, and use mitigating strategies as appropriate e.g. convoys during windows of safety. In the opinion of the authors, the true AHI on the Milford Road is closer to 0.5 to 0.35 of the calculated value, at approximately 0.98 to 1.4. This opinion is based on observations of the current contractor's practices during times of increasing hazard. The contractor maintains regular road patrols, reducing the possible waiting times to less than 1 hour, and maintains a snow free road, increasing average speed of vehicles while reducing the stopping distances, which were based on snow covered roads. Elimination of all hazard can be expensive, and complete control of avalanches and of traffic movement is not possible. A minimum avalanche hazard must therefore be tolerated. Schaerer(1989) noted that experience showed that people can accept an AHI of 1. Further reduction of the AHI would usually require control measures that are economically not justified, or would demand unacceptably long traffic delays because of extended closure. Schaerer(1989) suggested that an avalanche hazard of 1 represents a risk that is 4-6 times lower than other risks to traffic.

Using the estimated frequencies of avalanche occurrence and size from Fitzharris and Owens(1980) and the values given above, the theoretically uncontrolled avalanche regime was calculated to have an AHI of 186.6, comprised of a P_m of 5.5 and P_w of 181.1. This value must be seen as a minimum, as waiting times on an uncontrolled road could easily exceed 2 hours, and vehicles would likely stop more frequently for photo opportunities. According to the North American practice to group highways with respect to the avalanche hazard, the Milford Road would now rate at a high hazard if uncontrolled. High hazard is suggested to require full avalanche control, artificial release, avalanche protection structures and an avalanche forecaster. A full avalanche control programme, with artificial release of avalanches, and an avalanche forecaster has been in place since 1984, since the inception of the avalanche programme. An avalanche protection structure was build at the eastern end of the Homer tunnel, but a 100m section was destroyed by an avalanche in 1945 and an event in October, 1996 damaged the remaining section (Conway et al., 2000). The high hazard rating is reflected in the recent work undertaken for a scoping exercise for an extension to the Homer tunnel, thereby eliminating risk from the East Homer and McPherson avalanche paths (URS, 2004). The AHI analysis suggests that the Transit New Zealand Milford Road Avalanche Programme is responsible for the reduction of at least 183 in the AHI.

Sensitivity analysis found that the AHI equation is most strongly influenced by parameters that affect the P_w component, which is mostly controlled by the length of the waiting queue. The AHI increases sharply by increasing the waiting times. This can be reduced through regular road patrols. The relationship between waiting times and AHI is not linear as it depends on the relative hazard posed by each path and the spacing between them. The AHI can also be sharply reduced through the use of buses, by decreasing the total number of vehicles on the road per km. This is especially true for waiting traffic where the same number of people on buses results in a significantly shorter queue than the same number in individual cars. Use of buses also insures a greater adherence to the no stopping rules and allows for easier ongoing education.

4.2 PDI Results

Using the modified equations 4 and 5, of Wilhelm(1998) and Margreth et al.(2003) and the new weightings, the PDI of the controlled and theoretically uncontrolled avalanche regime on the Milford Road for the present (2005) situation has been calculated. Both of these analyses have been undertaken using the same input parameters:

$C{:}B$ = 0.86 : 0.14 (URS, 2004)
β_B = 30 (est., Wilkins pers. comm., 2004)
β_C = 1.6 (Margreth et al., 2003)
V = 40 kmh^{-1} (Fitzharris and Owens, 1980)
λ_{i3} = 0.05 (Schaerer, 1989)
λ_{i4} = 0.25 (Schaerer, 1989)
λ_{i5} = 0.50

Based on the database of all avalanche occurrences on an open road and using the above parameters, the current controlled avalanche regime was calculated to have a PDI of 5.4×10^{-5} for a commuter with 2 passes per day and 1.6×10^{-4} for a member of the road crew with 6 passes per day. While the PDI for a daily commuter on the Milford Road, such as helicopter pilots, bus drivers and fishermen, will be the same as for a tourist on any given day, if annualised a tourist will have a significantly lower PDI than the daily commuters. The intention of this analysis is to calculate the PDI for the most at risk public group of the population. The collective risk was calculated at 0.061 deaths per year. This must be viewed as an absolute maximum on the controlled Milford Road, as the speed of traffic is often greater than 40 kmh^{-1} and the current road operators are very aware of times of increasing hazard while the road is open, and use mitigating strategies as appropriate e.g. convoys. Weir(1998) estimated much higher PDI equivalents at approximately ten times the risk associated with normal road travel, or equivalent to activities such as white-water rafting.

Using the estimated frequencies of avalanche occurrence and size from Fitzharris and Owens(1980) and the above parameters, the theoretically uncontrolled avalanche regime was calculated to have a PDI of 6.8×10^{-4} for a commuter with 2 passes per day and 2.1×10^{-3} for a member of the road crew with 6 passes per day. The collective risk was calculated at 0.774 deaths per year. This suggests that the Transit New Zealand Milford Road Avalanche Programme is responsible for the reduction of at least one order of magnitude in the PDI.

Sensitivity analysis found that the PDI equation is most strongly influenced by the speed of the moving vehicle. As the speed increases the PDI decreases, as faster moving vehicles are exposed to the hazard for a shorter period of time. The probability of death for each avalanche type λ_{ij} has also been varied. PDI for commuters and road crew, and collective risk did change as a result of these modifications, but remained within the same orders of magnitude. If the PDI method accounted for waiting traffic, then a parameter controlling this would defiantly influence the outcome of the equations the most. A more detailed description of the sensitivity analyses for PDI and AHI will be published in the near future.

4.3 Risk evaluation and comparison

Having determined the level of risk currently experienced on the Milford Road in terms of the AHI, PDI and collective risk, this can now be compared to other avalanche prone roads around the world.

Using the equations of Schaerer(1989) the AHI on the Milford Road can be compared to that of Rogers Pass, B.C., Canada. Table 1 shows the comparison of AHI before any control, after structural control (not including artillery), and the residual AHI for the Milford Road and Rogers Pass. While the AHI has been modified since its inception and the method used by Stethem et al.(1995) for Rogers Pass is not clearly outlined, these values can still be used for the basis of a conservative comparison. *T* has been standardised to 1000 for all roads to permit comparison of the effect of the physical attributes of the avalanche paths, and therefore not just highlight the difference in traffic volumes. When the AHI after structural control is considered, based on a T = 1000, the Milford Road has a significantly higher AHI than the historical values for Rogers Pass (Table 1). It is interesting to note that per 1000 vehicles the AHI, after structural control, has decreased at Rogers Pass, clearly showing the effect of increasing the number of structures on the road. The Milford Road currently has no structures to mitigate the effect of an avalanche. When the residual AHI is considered, again based on T = 1000, the Milford Road has a much lower AHI than the historical values for Rodgers Pass.

The effectiveness of the management and forecasting practices (following structural control) of each avalanche programme can also be compared (Table 1). The AHI after structural control compared to the residual AHI is reduced by 179 or 84% on the 1992 Rogers Pass, compared to 184 or 98% on the present (2005) Milford Road. However, when comparing the uncontrolled AHI, Rogers Pass clearly has a much more serious avalanche problem with a very high AHI, especially for the 1987 calculation.

Schaerer(1989) showed that people can accept an AHI of 1, and reducing this value would usually require control measures that are economically not justified, or would demand unacceptably long traffic delays. The calculations shown in Table 1 all show the residual AHI to exceed 1, suggesting that, according to the criterion of Schaerer(1989), the AHI is unacceptable on all these roads. However, the true AHI on these roads is lower than the calculated AHI, as the theoretical frequency of encounters has been found to be far greater than the observed number (Schaerer, 1989), and current road operators are aware of times of increasing hazard while the road is open, and will use mitigating strategies to reduce the hazard.

Using the modified equations of Wilhelm(1998) and Margreth et al.(2003), the collective risk on the Milford Road can be compared to several pass roads in Switzerland. While a direct comparison of the Milford Road will not be entirely equivalent (as the modified PDI calculations use higher probabilities of death for an avalanche), it will provide a basis for a conservative comparison. When the initial collective risk (ICR) is considered, based on a T = 1000, the Milford Road is subject to significantly higher risk than three main pass roads in Switzerland; Flüela, Lukmanier and the Gotthard (Table 2). T has been standardised to 1000 for all roads to permit comparison of the effect of the physical attributes of the avalanche paths, rather than highlighting the difference in traffic volumes. When the residual collective risk (RCR) is considered, again based on T = 1000, the Milford Road has only marginally higher risks than the Flüela and Lukmanier pass roads. When this is compared to the relative accessibility of the roads, the Milford Road is seldom closed more than 20 days year^{-1}, while the Flüela (between 1964 and 1971) was closed a minimum of 95 days year^{-1}, and the Lukmanier (between 1965 and 1997) was closed a minimum of 68 days year^{-1} (Margreth et al., 2003). The RCR on the Milford Road, as controlled by the avalanche programme, is only 8% of the ICR. This is significantly less than 19% for the Flüela and 14-25% for the Lukmanier, which is controlled by artificial release on the northern side. The Gotthard however, has a very low RCR, at only 2% of the ICR, which reflects the long winter closures (> 142 days year^{-1}), thereby almost eliminating all risk.

	Rogers Pass, 1974 (Avalanche Task Force, 1974)	**Rogers Pass, 1987** (Schaerer, 1989)	**Rogers Pass, 1992** (Stethem et al., 1995	**Milford Road, 2005** (This study)
Endangered road (km)	36	36	36	29
No. of avalanche paths	65	65	130	50
Winter Traffic (vehicle d^{-1})	905	1700	2300	406
AHI – with no control	335	1004	850	187
AHI – after structural control (SC)	174	235	214	187
AHI – after SC.,(T = 1000)	192	138	93	461
AHI - residual, (T = 1000)	?	8.8	15.2	6.9
AHI - residual	?	<15	<35	<2.8

Table 1: AHI before and after control for Rogers Pass and the Milford Road.

Table 2: Collective risk before and after control. Modified from Margreth et al.(2003).

	Flüela	**Lukmanier**	**Gotthard**	**Milford 2005**
Affected road (km)	19.3	25	24	29
Endangered road (km)	10.1	13.6	15.7	29
No. of avalanche paths	47	94	55	50
Winter Traffic (vehicle d^{-1})	1000	1000	6000	406
Closed days (d $year^{-1}$)	> 95	> 68	> 142	< 20
Initial collective risk (ICR) (deaths $year^{-1}$)	0.70	0.51	5.54	0.77
ICR standardised to T = 1000	0.70	0.51	0.92	1.90
Residual collective risk (RCR) (deaths $year^{-1}$)	0.13	0.07-0.13	0.11	0.061
RCR standardised to T = 1000	0.13	0.07-0.13	0.02	0.15

Wilhelm(1999 [in] Margreth et al., 2003) suggests that a driver on a public road with a low probability of avoiding an avalanche should have a PDI lower than $1x10^{-5}$. This is compared to a PDI of $8.3x10^{-5}$ for a traffic accident in Switzerland (Margreth et al., 2003). NGI(2003) suggests that an avalanche encounter should be viewed as an 'obligatory' or involuntary risk, and as such should have a 1:10 ratio of the traffic accident rate. In Norway, the traffic accident rate is approximately 400 for a total population of 4 million ($1x10^{-4}$), so the avalanche rate corresponds to approximately 1 per 100,000 inhabitants or $1x10^{-5}$. New Zealand in 2002, with a similar population of 3,939,100 and road traffic fatalities of 404 (Land Transport Safety Authority, 2003) had a PDI for road traffic fatalities of $1.03x10^{-4}$, similar to that of Norway. Applying the approach taken by NGI(2003) suggests that the Milford Road should have a PDI from avalanche risk no greater than $1.03x10^{-5}$. The risk analysis provides a higher number at 5.4×10^{-5} for a commuter with 2 passes, based on the assumptions listed. However, the acceptable PDI from a hazard, other than driving, on a road in New Zealand may have a higher tolerable limit, than in Norway.

5. CONCLUSIONS

Risk evaluations in terms of the AHI and PDI have been undertaken on the Milford Road for the present avalanche risk on the highway. This has been compared to the risk of a theoretical, uncontrolled avalanche regime, but with traffic at 2005 levels. The AHI analysis shows the theoretical uncontrolled AHI to be very high, with an AHI of 186.6. The avalanche programme's control reduces the present avalanche risk to approximately 0.98 to 1.4. The residual AHI for the Milford Road is significantly lower than that for Rogers Pass, even when standardised for T = 1000. In terms of calculated residual AHI, the Milford Road may have an unacceptable level of risk, but this is reduced to an acceptable level in practice through regular road patrols, high bus usage and effective avalanche safety management. Sensitivity analysis found that the AHI equation is most strongly influenced by parameters that affect the P_w component, which is mostly controlled by the length of the waiting queue. This can be reduced through the use of buses and maintaining regular road patrols.

The modified Wilhelm(1998) and Margreth et al.(2003) PDI analysis shows the theoretically uncontrolled PDI to be very high at $6.8x10^{-4}$ for commuters and $2.1x10^{-3}$ for a member of the road crew, and completely unacceptable. The avalanche programme's control reduces the PDI for avalanche risk to 5.4×10^{-5}, which is higher than the suggested PDI for avalanche risk on roads in Switzerland and Norway, but may still be acceptable in New Zealand. Collective avalanche risk on the Milford Road also shows the theoretically uncontrolled risk to be very high, and unacceptable. The residual collective risk is slightly higher than similar roads in Switzerland, but the Milford Road is far more accessible, with fewer closed days.

To maintain this level of risk with increasing traffic volumes, continued improvement in the understanding of avalanching and avalanche safety management is required to maintain an effective avalanche programme.

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