Winter opening of high alpine pass roads – analysis and case studies from the Swiss Alps

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Abstract: The pass roads across the Swiss Alps are of high importance for the transportation of persons and goods. Due to the alpine topography most of the pass roads are permanently closed in winter, mainly because of avalanche danger. In this paper a methodology is provided to analyse the risks for a winter opening of a pass road and to determine necessary protection measures. At first the avalanche situation is investigated by an inventory of the existing avalanche paths. Then a risk analysis for an initial state without any safety measures is performed. If the risks for the public and individuals are not acceptable then protection plans taking into account preventive closures, artificial release or structural measures must be established. The acceptable risk is defined by the estimated number of avalanches blocking an open road. The methodology was developed and adjusted with data from Flüela Pass, where over a distance of 19.3 km 47 avalanche paths endanger the road. The application of the methodology is finally demonstrated with the case studies of the Lukmanier and Gotthard Passes. For both pass roads, which were permanently closed in the past winters and which are endangered by 94, respectively 55 avalanche paths, the SLF compiled different protection plans for a possible winter opening.

Keywords: avalanche protection; snow avalanche; traffic risk; risk management.

1 Introduction

The pass roads across the Swiss Alps are of high importance for the transportation of persons and goods. Due to the alpine topography most of the pass roads are permanently closed in winter because of avalanche danger. The investigation of the possibilities for a winter opening of pass roads has a long tradition at the SLF. The usual approach was to elaborate on the base of the avalanche register a danger map which showed the different degrees of winter safety of the pass road. The protection goal was in general to achieve a limited winter safety, i.e. to control the avalanches with a frequency of less than 30 years by structural measures (Sommerhalder 1972). At this high safety level road closures only had to be foreseen in extraordinary avalanche situations (typically on 1 to 3 days per year).

2 Methodology for avalanche risk assessment on pass roads

Today the resources for structural avalanche protection measures for roads are very limited. Temporary measures, such as warning, temporary closure or artificial avalanche release are therefore of much higher importance. The purpose of the risk based method presented in this paper (Figure 1) is to provide decision makers with all technical information required in a simple form. At first the avalanche situation on the pass road is investigated mainly by an inventory of the existing avalanche paths. Then a risk analysis for an initial state (without any safety measures) is performed. If the risks for the public and individuals are not acceptable then protection plans taking into account

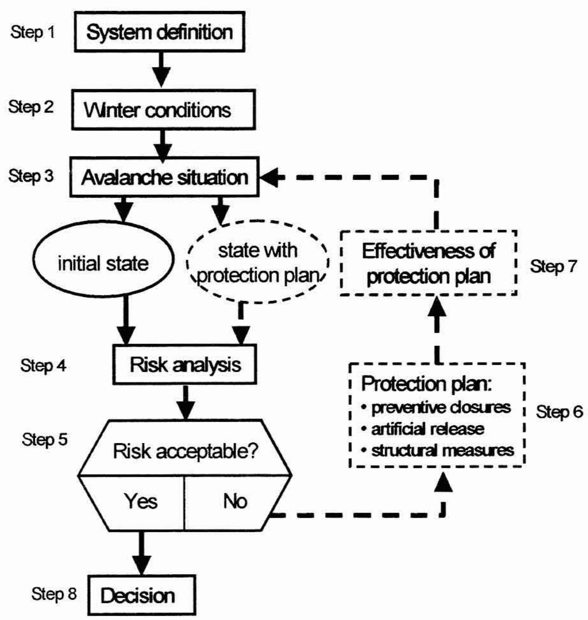

Figure 1: Elements for avalanche risk assessment on pass roads.

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preventive closures, artificial release or structural measures must be prescribed. Finally, the reduced risk should satisfy the acceptable risk level. The presented methodology for avalanche risk assessment was developed and adjusted with data of Flüela Pass (Christen 1998, Wilhelm 1998). In the paper the application of the methodology is demonstrated on two case studies: the Lukmanier and Gotthard Pass (Figure 2).

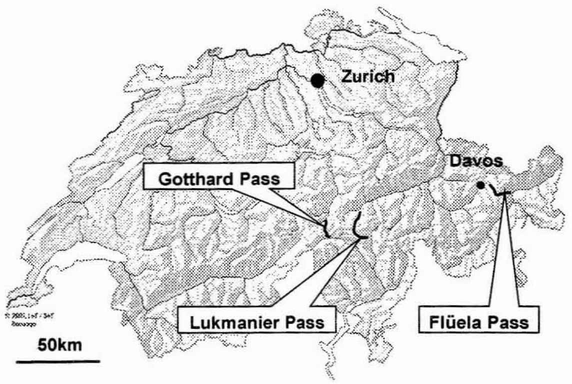

Figure 2: Map of Switzerland with investigated pass roads.

3 Overview of the study area of the Flüela Pass

The Flüela Pass (2305 m ASL), which leads from Davos (1540 m ASL) to the Engadin valley (1430 m ASL), was closed in winter until 1971 for 156 days on average. Between 1971 and 1999 the pass road was kept open in winter. A protection plan consisting of temporary closures and artificial release was applied. After 1999 the pass road was again permanently closed in winter, because a railway tunnel was opened which offers a shuttle service for vehicles. Over a distance of 19.3 km the pass road is crossed by 47 avalanche paths on a total length of 10.1 km. According to the avalanche register, 38 spontaneous and 27 artificially triggered avalanches hit the road each winter (Table 1). The maximum avalanche activity was in winter 1991/92 when 117 events blocked the road. No structural measures protect the road. The mean consumption of explosives was between 500 and 1000 kg each winter. The cost to keep the pass road open in winter were on average 0.5 million SFr, whereof 80% was for the removal of snow and avalanche deposits. With this protection plan, the closure was reduced to 26 days on average. The length of the closures varied from a few hours to weeks. The average daily traffic in winter (WDT) was 1000 vehicles per day.

4 Development and adjustment of the methodology with data from Flüela Pass

Step 1: System definition

The investigated system must be defined to which the risk is referred. In the proposed methodology only the avalanche risk is considered, risk due to rock fall, icing or snow drift were neglected.

Step 2: Winter conditions

The decisive weather situations, the depth of the snowpack and the new snow heights are used to define the winter conditions. The combination of snowfall and avalanche activity was analysed at the Flüela Pass. 69% of all avalanches (natural and artificially triggered) were released during or after a snowfall of more than 10 cm (measured at the foot of the pass) and 31% without snowfall (Table 1). In the natural avalanche activity the number of spontaneous avalanches due to snowfall equals the number without snowfall.

Table 1: Flüela Pass, mean number of avalanches blocking the road per year, data from 1986-1994

Total number of avalanches	65 (100%)	
Avalanches due to snowfall (per day >10 cm measured at the foot of the pass)	45 (69%)	
- Spontaneous release at most 1 day after snowfall		20
- Artificial release		25
Avalanches without snowfall	20 (31%)	
- Spontaneous release after more than 1 day after snowfall (e.g. warming)		18
- Artificial release		2

Step 3: Avalanche situation

The identification and characterisation of the different avalanche paths along the pass road is fundamental. A map with the location of all avalanche paths is mandatory. Usually very limited information regarding the avalanche activity is available. Therefore the necessary data about terrain, vegetation and climate must be collected through on site observations. The interrogation of the road maintenance staff can also provide useful information concerning the avalanche activity. A map with the slope inclination is often a helpful tool. The following data of every single avalanche path are of importance:

- Avalanche type: According to the size of the starting zone and the nature of the topography, the type, volume and intensity of the avalanches can be assessed. The consequence of small or light powder avalanches to the traffic is relatively small compared to heavy dense flow avalanches, which can block the road with more than 1 m of snow.

- The slope exposition is of importance for the artificial avalanche release and for the begin of a closure. Avalanches from east to south exposed slopes can endanger roads in spring situations in the morning already. In typical spring situations the Flüela Pass road was often closed between 11 am and 6 pm due to the hazard of wet snow avalanches.
- Ground surface roughness: Coarse boulders with a diameter of at least 50 cm or bushes of at least 100cm height reduce the avalanche activity, particularly in early winter.
- The return period (T) of a specific avalanche path correlates to the slope inclination in the starting zone and track, to the elevation, to the terrain features and to the surface roughness. At the Flüela Pass the most frequent avalanche paths are characterised by an average slope inclination of more than 30° between fracture line and road, an average slope inclination in the last 200 m above the road of more than 28°, no bushes or trees in the path and a vertical drop of less than 500 m. At the Flüela Pass 60% of the avalanche paths have a mean incline of more than 28° in the last 200 m above the road. For an average slope angle of at least 30° a mean return period of at least 2 years can be assumed. In the most frequent avalanche paths on the Flüela Pass the road was blocked 6 times per winter on average. It was assumed that without artificial release, on average 47 avalanches would block the road per year. Figure 3 shows how many times in a 10-year period the road was hit in the different avalanche paths. The frequent avalanche paths are the most important ones for the risk calculation.

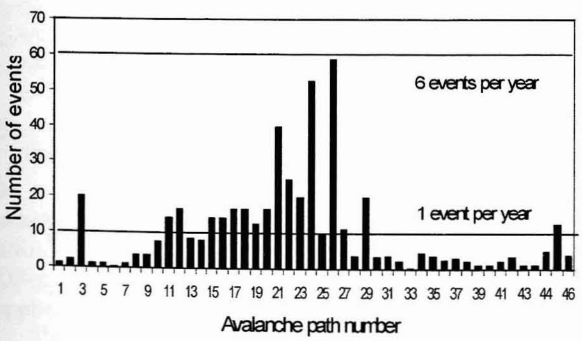

Figure 3: Numbers of avalanches hitting the Flüela Pass road in the single avalanche path in 10 years.

- The maximum width of road that can be covered with avalanche snow (g_{max}) can be assigned from the boundaries of the terrain or from the trim line of the vegetation. Also the results from numerical avalanche simulations can be helpful.
- The mean width of the avalanche crossing the road (g) corresponds to the mean value of all avalanches in a path. The difference between the maximum and the mean width is bigger in an unconfined path compared to a channelled path. The analysis of all avalanche paths at the Flüela Pass shows that the mean width is 36% of the maximum width.
- During field visits, the effectiveness of existing and the feasibility of new protection measures have to be checked. With regard to artificial release, the existing damage potential to power lines, buildings or protecting forest has to be mapped.

Step 4: Risk analysis

Risk can be defined as the product of the probability of an avalanche event and its consequences (Bohnenblust 1987). On a pass road the public authority is mainly concerned about the total damage, which is described as collective risk in terms of expected number of fatalities per year. This value is often used in annual accident statistics. Not to be forgotten is the individual risk, especially from the road maintenance crew, because these people are more exposed to avalanche danger.

The collective risk, which represents a mean value, is calculated at first for an initial state, that is without any safety measures. We assume that the road would be open and driveable throughout the winter. The parameters given in Figure 4 are relevant to comprehend traffic risk. The avalanche probability is calculated as the reciprocal of the mean return period T. The probability of the presence of vehicles is given by the average winter daily traffic (WDT), the mean width of the avalanche crossing the road (g) and the speed of

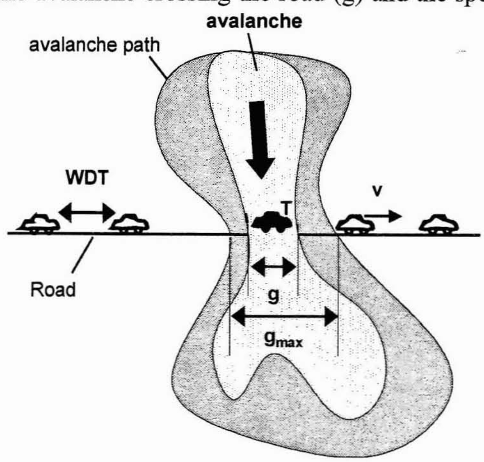

Figure 4: Model for recording the avalanche risk along a pass road (Wilhem 1998).

Table 2: Flüela Pass, collected data and calculation of collective risk

Avalanche path		Collected data							Collective risk
Nr.	Name	Avalanche type	Artificial release	$g_{i,max}$ (km)	g_i (km)	λ_i (1)	T_i (years)	v_i (km/h)	R_o (death/year)
....	....								
25	Suot Pedra quadra	dense	yes	0.1	0.05	0.18	0.96	50	0.013
26	Champ Lönch	dense	yes	0.29	0.07	0.18	0.17	50	0.099
27	Champatsch	dense	yes	0.63	0.27	0.18	0.9	30	0.120
....	....								

vehicles (v) crossing the avalanche path. The risk is calculated for each avalanche path and then summed up to obtain a value for the whole pass. According to Wilhelm (1998) the collective risk (death per year) on a road crossed by several avalanche paths is calculated with the mentioned parameters as follows (Table 2):

$$R = \frac{WDT \cdot \beta}{24h} \sum_{i=1}^{n} \frac{g_i}{T_i \cdot v_i} \cdot \lambda_i \qquad \text{(deaths per year)}$$

i=1, 2,....n avalanche paths

- The WDT can be taken from traffic census.
- The mean number of passengers β (people/vehicle) is typically 1.6.
- The probability of death in vehicles λ was taken from statistical data (Table 3). In the Swiss Alps between 1946 and 1999 167 passengers were buried by avalanches in their vehicles, of whom 30 persons or 18% died.

Table 3: Avalanche burials in vehicles on roads in Switzerland (data from 1946 to 1999)

	buried	uninjured	injured	dead
Number of persons	167	86	51	30
%	100	51	31	18

The total collective risk in the initial state without any safety measures amounts at the Flüela Pass to 0.7 deaths per year. An important point is that risk peaks which can be 10 to 100 times higher than the mean value e.g. because of a much higher WDT on weekends or a queue of waiting vehicles are not considered. The queuing problematic requires extensive model assumptions, see Schaerer (1989) and Wilhelm (1999).

Step 5: Acceptable risk

At the Flüela Pass the residual risk amounted to 6 to 8 avalanches hitting the open road which corresponds to 0.13 deaths per year. Between 1971 and 1999, 5 persons were killed by avalanches in two accidents and 2 persons from the maintenance crew were injured during snow removal work. In Table 4 the initial collective risk of the Flüela Pass is compared to the Lukmanier and Gotthard Passes (see section 5.1 and 5.2).

In a court expertise after the fatal accident of 1992 (SLF 1992), the residual risk at the Flüela Pass was considered to be too high. No improvement of the protection plan was made because the permanent closure of the pass road was fixed for winter 1999/2000.

Schaerer (1989) described the avalanche risk on a road by the avalanche hazard index. He concluded that an avalanche hazard index of 1 could be accepted. A hazard index of 1 would be present on a road with a WDT of 750 vehicles per day, a mean speed of 80 km/h, stopping distance of 30 m, one light-snow avalanche with a width of 30 m and one deep-snow avalanche with a width of 80 m per year. The corresponding risk is 0.024 deaths per year.

Weir (1998) compared the avalanche risk with

Table 4: Risk on the Flüela, Lukmanier and Gotthard Pass roads

Pass road	Road length	Endangered road length	Number of avalanche paths	Mean number of avalanches blocking the road per year over a distance of 10 km	WDT	Initial collective risk without any safety measures	Risk based on WDT of 1000 vehicles per day	Residual risk
	(km)	(km)	(1)	(1/year and 10km)	(vehicles per day)	(deaths per year)	(deaths per year)	(deaths per year)
Flüela	19.3	10.1	47	24.4	1000	0.70	0.70	ca. 0.13
Lukmanier	25.0	13.6	94	21.6	1000	0.51	0.51	See case study 1
Gotthard	24.0	15.7	55	37.5	6000	5.54	0.92	See case study 2

Table 5: Acceptable risk as a function of road type, winter average daily traffic WDT and avalanche activity in an initial state without a protection plan

Road category	WDT (vehicles per day)	Number of avalanches per year blocking a road over a distance of 10 km *(initial state without protection plan)*	**Acceptable number of avalanches per year blocking an open road over a distance of 10 km** *(final state with protection plan)*
Main road of national interest (e.g. Gotthard)	>1000	20-30 per 10 km road	**0-1 per 10 km road**
Regional road of local interest (e.g. Flüela, Lukmanier)	<1000	20-30 per 10km road	**1-2.5 per 10 km road**

average traffic risks. In Switzerland in 2000, 1.7 people were killed in traffic accidents per 100 million vehicle kilometres on rural roads (BFU 2002). If we sum up the vehicle kilometres covered in winter at the Flüela Pass this corresponds to 0.051 traffic deaths per year. An acceptable risk level may be a little lower, because the acceptability to die in an avalanche on an open road compared to die in a car crash might be lower, due to the lower level of self-determination.

An avalanche blocking the open road seems to be an easily understandable term to describe the residual risk. We think that at the Flüela Pass a residual risk consisting of 3 to 5 avalanches per year blocking the open road could be tolerated. If in the 3 most frequent avalanche paths at Flüela Pass one avalanche would block the road each winter, then the resulting residual risk is 0.03 deaths per year. To establish on a general level an acceptable risk, the road category, the traffic quantity and the number of avalanche paths also have to be considered. On main roads with a WDT of more than 1000 cars and a natural avalanche activity of 20 to 30 blockages over a distance of 10 km a protection plan with 0 to 1 blockages of the open road per year over a distance of 10 km could be tolerated. For regional roads with a WDT smaller than 1000 cars, 1 to 2.5 avalanches per year blocking the open road seem to be acceptable (Table 5).

Step 6: Protection plan for a pass road

The goal of an avalanche protection plan is to attain an acceptable risk level for both the public and the maintenance crew. Therefore preventive closures, artificial release and structural measures are common. Often a combination of the different measures is applied.

The estimation of the necessary temporary closure days in the scope of a protection plan is difficult. A road must be closed if a blockage by an avalanche must be expected. In practice a road closure is often imposed by the safety service after a first precursory avalanche has been observed. Continuous surveillance and local experience are therefore fundamental. The following factors can be helpful for a rough estimate of the necessary closure days on a pass road:

Total closure time in the past: The average length of the permanent winter closure represents the severity of the winter on a pass and gives an upper limit for the number of closure days (Table 6).

Table 6: Length of permanent winter closure at the investigated pass roads

Pass road	Time period	Average closure (days)	Min. closure (days)	Max. closure (days)
Flüela	1964-1971	156	95	215
Lukmanier	1965-1997	150	68	210
Gotthard	1934-2001	198	142	247

Avalanche bulletin: The avalanche bulletin issued by the SLF for whole Switzerland describes in winter the avalanche hazard daily. According to the European avalanche hazard scale with five grades, roads are hardly endangered by spontaneous avalanches at grade 2 ("moderate"). At grade 3 ("considerable") the risk is much higher especially for exposed roads. If a road is located in very steep terrain, dangerous avalanche activity can develop at grade 2. For a rough estimation,

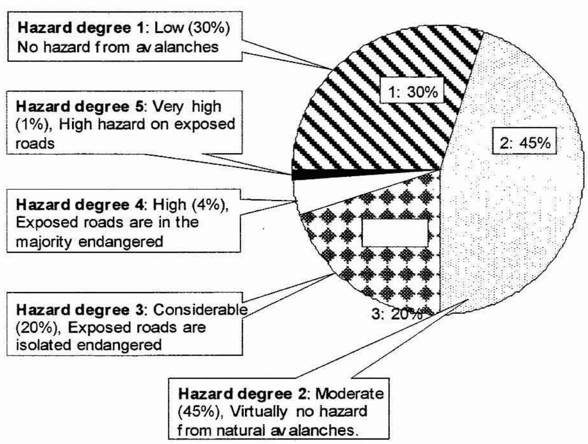

Figure 5: Distribution of the different hazard degrees of the avalanche bulletin and consequences for roads.

it can be assumed that normally it is sufficient to close a road on days with a grade 3 and higher. On average in the Swiss Alps on 30% of the winter days the hazard grade is 1 ("low") and on 45% of the winter days 2 ("moderate") (Figure 5). If we assume a mean permanent closure of a pass road of 156 days (e.g. Flüela Pass) on average the necessary number of closure days varies from a minimum of 40 to a maximum of 110 days.

Local snow, weather and avalanche activity: The experience obtained from Flüela Pass shows that with a new snowfall of more than 15cm measured in Davos (1540m ASL) there is a high probability for avalanches hitting the pass road. On average 1.4 closure days were utilised per day with more than 15 cm new snow measured in Davos. In Davos on 9 days per winter a new snowfall of at least 15 cm is measured on average. The reason for the closure of Flüela Pass are given in Table 7. Half of the closure days resulted from heavy snowfall and the other half from small snowfall, warm periods or snow drift.

Table 7: Reasons for the temporary closure of the Flüela Pass

Heavy snowfall (per day >15 cm in Davos, 1540 m ASL)	53%
Light snowfall (per day <15 cm in Davos, 1540 m ASL)	14%
Warm periods	18%
Storm, snow drift, other reasons	15%

Step 7: Effectiveness of protection plan

Protection measures either reduce the probability of avalanche encounter or the probability of presence. At the Flüela pass the residual risk with artificial release and 26 temporary closure days consisted on average of 6 to 8 avalanches per year blocking the open road. This corresponds to a risk reduction of 82%. With the protection plan the collective risk could be reduced from 0.70 to 0.13 deaths per year. If no avalanche data are available, the risk reduction must be determined prospectively:

With artificial release and temporary closures a risk reduction of 80% to 95% is reasonable. Permanently installed release devices (e.g. GASEX or Wyssen Avalanche Tower) additionally increase the risk reduction.

Temporary closures without artificial release have a lower risk reduction, if the number of closure days is not changed. Wilhelm (1999) investigated for the Flüela Pass the correlation between risk reduction and number of closure days (Table 8). If the Flüela Pass road is only on days open with a hazard degree "low" which corresponds to 110 closure days a risk reduction of practically 100% can be assumed. With 11 closure days the risk reduction is reduced to only 40%.

Avalanche sheds provide a risk reduction of 100%, if the length of the shed is appropriate.

Supporting structures typically provide a risk reduction of 85% to 95%. The risk reduction depends mainly on the extent and height of the structures, but also on the topography below the protected area (Margreth 1996).

Table 8: Risk reduction as a function of temporary road closure without artificial release of avalanches (according Wilhelm 1999)

Road closure in (%) of maximal closure (days):	Risk reduction:
10 % (11 closure days)	40 %
30 % (33 closure days)	70 %
50 % (55 closure days)	90 %
100 % (110 closure days = maximal closure)	100 %

Step 8: Decision

A protection plan shows what can be achieved for a certain investment. For that purpose the remaining risk represented by the number of avalanches blocking the open road, the expected number of temporary road closures, the cost and investments and finally the determination of the cost-benefit of a protection plan are valuable. The decision makers will assess these points and take other factors, such as political criteria, into account.

5 Application of the methodology

5.1 Case study 1: Lukmanier Pass

Situation: The Lukmanier Pass (1972 m ASL) connects Curaglia (1332 m ASL) on the N-side with Campra near Olivone (1430 m ASL) on the S-side, over a distance of 25 km. Before 2000 the pass road was closed over a period of 5 months on average. In 1997 local representatives requested for the pass road to be kept open due the recent relatively mild winters and because of tourist interests. The SLF investigated the possibilities for a winter opening in 1998 (SLF 1998). Over a distance of 13.6 km the pass road is endangered by 94 avalanche paths. The Lukmanier area is situated on a weather borderline and receives precipitation from the NW and the S in comparison to the Flüela area, where precipitations from the NW dominates. In the Lukmanier area, a snowfall of more than 15 cm is observed in average on 10 days per winter.

Methodology: The inventory of the avalanche paths was assessed mainly by terrain and vegetation analysis. Avalanche records were only available for a small number of avalanche paths. The number of avalanche

Table 9: Proposed protection plans for a winter opening of the Lukmanier pass road

Protection Plan	Collective risk (deaths/year)		Residual risk (avalanches on open road/year)	Investments	Preventive closure days/year	Safety for maintenance crew
Initial state	0.51	(100%)	54	-	0	-
1: temporary closures	ca.0.07	(12-15%)	4-5	small	70	insufficient
2: temporary closures + artificial release	ca.0.13	(23-29%)	8-10	small	28	scarcely sufficient
3: prolonged temporary closures + improved artificial release (e.g. GASEX)	ca.0.06	(9-14%)	3-5	small-medium	32	sufficient
4: prolonged temporary closures + artificial release + structural measures in 10 avalanche paths	ca.0.04	(6-9%)	2-3	medium (ca. 20 Mio. SFR)	32	sufficient
5: full protection (10km of sheds)	ca.0	(0%)	ca.0	very large (ca. 250 Mio. SFR)	0	good

paths with a frequency lower than 1 year is similar to the Flüela Pass. However, the Lukmanier Pass has five times more avalanche paths with a frequency of more than 5 years. With a WDT of 1000 vehicles per day the initial risk without safety measures is with 0.51 deaths per year lower than on the Flüela Pass, but nevertheless not acceptable. Five different protection plans (Table 9) were investigated to keep open the pass road in winter.

Conclusion: The conclusion was that a winter opening of the Lukmanier Pass on the base of protection plans 3 and 4 is possible. The residual risk of 3-5, respectively 2-3 avalanches on the open road is acceptable for a 25 km long pass road with a WDT of estimably 1000 vehicles a day (see Table 3). Protection plan 1 provides an insufficient degree of safety particularly for the road maintenance crew. Protection plan 2 has a high residual risk which is barely acceptable.

Decision: The political decision-makers decided to open the pass road in winter during a 5-year test period on the basis of a combination of protection plans 1 and 2. In addition, they decided not to use the artificial release on the south side of the pass because of the high damage potential. A snow safety service was founded, which is responsible for the opening of the pass road. Unfortunately, winter 2000/01, the first winter when the pass was opened, was highly above average. The pass road had to be closed on 116 days. A total of 78 avalanches hit the road. On 2 days, 4 avalanches blocked the open road, but no vehicles were affected. The traffic volume was much smaller compared to the assumed WDT of 1000 vehicles. The initiators were not all content with this first winter, particularly because of the very short opening periods.

5.2 Case study 2: Gotthard

Situation: In mid October 2001, the Gotthard road tunnel was partially destroyed by a disastrous fire in which 11 people were killed and consequently the tunnel had to be closed. The Gotthard road is the most important North-South traffic axis in the Alps with an WDT of over 18'000 vehicles. The road authorities were concerned by the consequence of a long closure of the tunnel. The alternative was to use the pass road, which is usually closed in winter over 198 days. The SLF was charged to investigate the possibilities for a winter opening (SLF 2001).

Methodology: The Gotthard Pass (2109m ASL) connects Hospental (1452 m ASL) on the N-side and Airolo (1141 m ASL) on the S-side. Over a distance of 24 km the road is endangered by 55 avalanche paths on a total length of 15.7 km. Snow is very abundant in the Gotthard area. On the pass on 27 days a snowfall of at least 15cm was measured in the past. No avalanche records were available. The most risky road sections were found on the south side of the pass where on a distance of 3.5 km the slope above the road is more than 28°. The Gotthard Pass has 25% more avalanche paths with a frequency of less than 1 year compared to the Flüela and Lukmanier Passes. With an estimated WDT of 6000 vehicles a collective risk of 5.5 deaths per year results for an initial state without any safety measures. This risk is 10 times higher in comparison with the Lukmanier Pass (Table 4). Because of the high traffic volume, risk peaks due to waiting vehicles additionally increase the risk. Three protection plans (Table 10) were presented on the basis that due to the tight schedule, structural measures are no option:

Conclusion: The analysis showed that even with the investigated protection plans, a very high residual risk remains. We concluded that a permanent winter opening of the Gotthard Pass road is only possible with extensive structural measures because of the very high risk involved. We therefore proposed to realize protection plan 1, i.e. a delay of the permanent winter closure.

Decision: The political decision-makers decided to leave open the pass road according to protection plan 1

Tab. 10: Proposed protection plans for a winter opening of the Gotthard Pass road

Protection Plan	Collective risk (deaths/year)		Residual risk (avalanches on open road/year)	Investments	Closure days/year	Safety for maintenance crew
Initial state	5.5	100%)	90	-	0	-
1: Delay of the permanent winter closure	ca 0.11	(2%)	1-2	very small	150	sufficient
2: temporary closures + artificial release on the N-side	ca.0.83	(15%)	6-10	small	90	insufficient
3: temporary closures + artificial release on the N- and partly on S-side	ca.0.55	(10%)	4-8	small	70	scarcely sufficient

as long as possible. A safety concept was established by the SLF, consisting of additional snow observation fields and a special avalanche bulletin for the Gotthard pass. Fortunately the begin of winter 2001/2002 was below average so that the hazard degree was mostly low. The pass road only had to be closed for very short time. During November and December on average 4300 and at maximum over 10'000 vehicles passed the Gotthard Pass per day. On 21st December 2001 the road tunnel was reopened and the pass road was consequently closed.

6 Discussion

In this paper a methodology for a simple risk-based analysis of high alpine pass roads was presented and applied to the Lukmanier and Gotthard Passes, which were permanently closed during the past winters. The methodology allows the identification of the most critical avalanche paths and the quantification of the risk for an initial state (without any safety measures) and for states with different protection plans. The methodology provides valuable suggestions to the decision-makers. The application of the methodology presupposes some practical experience, because much of the input data is based on estimates.

The methodology was developed and tested using the data from Flüela Pass. With additional and better data, improvements would be possible. Important points are the assessment of the avalanche return period without avalanche data, the effectiveness of road closure or artificial release and especially the quantification of an acceptable risk level. The suggested acceptable risk must be proved by further investigations and practical application.

The better the avalanche and traffic data are, the more sophisticated the possible analysis. It is important to keep an avalanche register containing at least the date, width and mean height of deposit, cause for release and status of the pass road. For detailed analysis, risk peaks should be considered. Finally, in order to compare the proposed methodology, the avalanche-hazard index proposed by Schaerer (1989) could be applied to the three investigated pass roads.

7 References

BFU, 2002: Statistik 2001, Unfallgeschehen in der Schweiz. Verunfallte pro 100 Mio. Fahrzeugkilometer nach Ortslage. Schweizerische Beratungsstelle für Unfallverhütung bfu, Bern.

Bohnenblust, H., 1987. Risk analysis and avalanche safety. IAHS Publication No.162, p.653-664.

Christen, H.R.; 1998: Lawinenkataster Flüelastrasse 1986-1998, Aufsichtstelle Winterdienst Flüelapass.

Margreth, S., 1996: Experiences on the use and the effectiveness of permanent supporting structures in Switzerland. Proc. ISSW 1996, Banff, p.233-238.

Schaerer, P., 1989. The Avalanche-Hazard Index. Ann. Glaciol., 13, p.241-257.

SLF, 1992: Tödlicher Lawinenunfall vom 1. Mai 1992 am Flüelapass. SLF Expert Report 92.08. Author: Meister, Davos.

SLF, 1998: Offenhaltung der Lukmanierstrasse im Winter. SLF Expert Report 98.01. Author: Margreth, Stoffel and Wilhelm, Davos.

SLF, 2001: Offenhaltung des Gotthardpasses im Winter 2001/2002. SLF Expert Report 2001.32. Author: Margreth et al., Davos.

Sommerhalder, E., 1972: Ablenkverbau. Lawinenschutz in der Schweiz. Beiheft Nr.9 zum Bündnerwald, Chur, p. 155-169.

Wilhelm, C.; 1998. Quantitative risk analysis for evaluation of avalanche protection projects, Norwegian Geotechnical Institute Publication Nr.203, Oslo, p.288-293.

Wilhelm, C.; 1999. Kosten-Wirksamkeit von Lawinenschutzmassnahmen an Verkehrsachen. Vollzug Umwelt, Praxishilfe, Bundesamt für Umwelt, Wald und Landschaft BUWAL, Bern, 110p.

Weir, P.L., 1998. Avalanche risk management – the Milford Road. In Owning the Future - Integrated Risk Management in Practice. D.Elms ed. Centre for Advanced Engineering, Christchurch. NZ, p.275-293.