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Road traffic and avalanches — methods for risk evaluation and risk management

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Foreword

This report subscribes to the NGI Strategic Institute Program ”20011001 — SIP6 snow-avalanche” financed by the Norwegian Research Council and to the EU project CADZIE “Catastrophic Avalanches: Defence Structures and Zoning in Europe”, part-financed under contract no. EVGI-CT-1999-0009. The report is a translation of the Norwegian version (NGI report 20001289-3), to English for the aforementioned project by Tim Gregory, NGI.

Summary

This report covers current methods that may be used to analyse and manage risks related to avalanches and road traffic. Avalanche types considered are primarily snow avalanches and rockslides.

Avalanches that impact road-users can lead to injury or loss of life. Avalanches that block roads, also lead to the disruption of planned operations, for example public or goods transport, with resulting economic consequences for the community. Blocked roads can also lead to indirect injury or loss of life due to the hindrance of emergency services.

We suggest that further work should concentrate on one or several roads in an avalanche prone region in co-operation with local road authorities. The development of procedures for mapping, identification and calculation of avalanche probabilities is important for quantitative risk analyses and decision making tools in connection with avalanches and road traffic.

Contents

Review and reference document

1 INTRODUCTION

1.1 Motivation

The purpose of this report is to give a general view of current methods applicable for the analysis and management of risk related to avalanches and road traffic, and elaborate these methods further by calculation examples. The avalanche types assessed are primarily snow-avalanches and rockslides.

Avalanches that hit road-users can lead to injury or loss of life. Avalanches that block roads, lead also to disruption of planned operations; for example, public or goods transport with resulting economic consequences for the community. Blocked roads can also lead to the indirect loss of life or of injury due to the hindrance of emergency services.

The risk road-users are exposed to is largely perceived as an involuntary risk, even though road traffic can be seen as ‘semi’-voluntary, when its purpose alone is seen as a leisure activity. Most of us however, are road-users of necessity and not because we see this in itself as a preferred leisure activity. Our participation in society, in one way or another, requires or demands us to be road-users. Moreover, travellers can only slightly influence the probability of being hit by avalanche.

For the majority of road-users, an avalanche and vehicle encounter is a low-probability incident. However, for individual road-user groups, for example commuters and road-maintenance personnel, the risk can be unacceptably high.

1.2 Main conceptions

The **consequence** of an incident can be defined in number of fatalities, number of seriously injured or monetary loss in terms of material damage.

The **probability** of an incident will always have a value between 0 and 1, (or between 0 % and 100 %), and will, in an avalanche context, often be associated to a point in time. In the case of repetitive phenomena, e.g. snow avalanches, it is normal to look at frequency, i.e. the average number of incidents per time-frame.

Risk is a combination of probability for an undesired incident and the consequences of this incident when it occurs. The consequences in this context relate to damage to life, property, material value, reduced ability to carry out planned activities or to technical malfunction. Regardless of damage type, it is acceptable to define risk as the ‘product’ of the consequence of an incident and the probability of the incident occurrence. Risk has therefore, in principle, no natural size limit between 1 and 0. A compound expression is frequently applied to indicate risk, which directly reflects which consequence one considers. An annual fatal risk of 0.001 related to avalanche would mean for example, that one person dies on average per 1000 years due to avalanche.

Risk analysis comprises the identification and characterization of what can go wrong and the quantification of the risk.

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Risk-management describes those measures which can be adopted to reduce the probability of an undesired avalanche (**cause-prevention**), or to limit damage effect (**consequence-reduction measures**). The risk level remaining after applied measures is termed **residual risk**.

2 RISK-ANALYSIS

The process of risk-analysis related to avalanches and road traffic can be presented thus:

1. **Problem approach and limitation:** Which timeframe should we consider? Which area should we study? Who or what should we estimate the risk for? What type of incident should we consider?
2. **Surveying/identification:** Which are the concrete incidents? An overview of possible scenarios derived from experience and analysis, (surveying of avalanche potential, general analysis).
3. **Consequence calculation:** What are the probable consequences that concern us in relation to the object(s) at risk?
4. **Probability and risk determination:** How great is the probability of a particular incident and what risk is connected to this incident?

2.1 Problem approach and limitation

In order for risk-analysis to be relevant and manageable, it is usually necessary to limit estimations by time and place. One should also decide who or what is at risk and which incidents should be considered.

2.1.1 Time

It is often prudent to try to estimate the frequency of undesired incidents. Statistics showing avalanche incidents and traffic density on a stretch of road hint at the annual probability of road-user/avalanche encounters. Frequency and probability are often seen as synonymous terms, however it may not always be relevant to a frequency, e.g. in relation to non-stationary stochastic processes.

In using frequency one would normally also assume stationary conditions over an unspecified time-frame, e.g. drastic climatic changes are usually not considered. Nevertheless, times may be of a different character and it is usual to differentiate between peace- and war-times. In some cases it is useful also to consider non-stationary conditions, for example, prognosticate changes in traffic volume.

When considering specific objects with a defined lifetime, it may be more useful to consider the probability of the undesired incident occurring within this timeframe. In the case of a large rockslide, which may be a single event in post-glacial times, it makes less sense to discuss frequencies. A more natural approach would be to explore how large the probability would be of a large rockslide release within a closer defined timeframe, e.g. the next 50 or 100 years. A stability analysis of the mountain slope might give an indication of this.

2.1.2 Area

Limitation of the aerial extent can also vary according to problem approach. In some cases, national or even global perspectives should be addressed. In cases relating to road traffic and avalanches one would normally consider transportation corridors or other stretches which are naturally or administratively bounded. Especially vulnerable, locally contained stretches will often be the subject of study. In some cases, it is advisable to divide such stretches into shorter segments, for example into unit lengths down to 10 m of road, see section 4.4.

2.1.3 For whom?

In the municipal risk- and vulnerability-analyses, it is usual to adopt a social perspective concerning risk (Directorate for Civil Defence and Emergency Planning, 1994). Here risk-analysis includes an assessment of consequences for human, economic and environmental factors for society as a whole. The risk for road traffic is included in this analysis and it is natural to examine the risk for road-users in general. One can also deal more specifically by considering the risk for a once-only road-user, a daily commuter or a road-maintenance worker. The probability, for example, of an express bus being hit may also be of interest, since this type of incident will be afforded much greater significance than that of a single car and driver being hit.

In general, the risk concerning the "average road-user" will not be sufficient as the basis for determining safety measures. It may often be more useful to estimate the individual risks run by persons who are more exposed to avalanche risk than the "average road-user". In many cases it is more natural to consider the safety of school buses or of road-maintenance crews, where the risk must be seen in relation to rules laid down in work environment laws and other regulations.

Finally, it may be of interest to examine the risk for communities that are cut off because of the only road is being blocked for a lengthy period.

2.1.4 Which incidents?

When dealing with avalanche and road traffic, there can be several types of undesired incidents. These can have both direct and indirect consequences for human life or death. For example, the extremely serious human consequences of a snow-avalanche or rock colliding with a car with passengers. Road blockages caused by avalanche can even result in a life or death situation for those thus isolated over a lengthy period. In addition, unforeseen road blockages may cause great economic stress, e.g. disruption of commercial transport.

In this connection we can initially single out the following undesired incidents:

1. direct encounters between avalanches and vehicles
2. avalanches which frequently block roads or incapacitate them for lengthy periods (traffic-artery blockage)
3. avalanches which cause damage to the body of road

Point 3 is not explored further in this report.

2.2 Surveying/identification

This process is normally initiated with a survey of avalanche potential along a particular stretch, together with the attainment of historical data. The significance of historical data in a survey is important since this often highlights particularly prone areas. Such data, however, are seldom neither consistent nor available and should be applied with some scepticism. When constructing new roads in previously undisturbed terrain, historical data may not be available.

Typically, studies will include:

1. Registration of earlier avalanche activity:
    - road-blockage reports (from highway authorities)
    - historical data (reports, articles, publications)
    - geomorphological interpretations (older avalanche deposits)
    - dating avalanche deposits (e.g. by carbon-dating analysis)
    - rock-fall evidence in asphalt
    - local knowledge (local people, highway authorities, superintendaries, police)
    - vegetation (type, age, damage)

2. Studies of avalanche potential, frequency and extent:
    - topographic parameters (slope angle, shape)
    - slope-stability (in rock and loose deposits)
    - meteorological conditions (return period for weather-related scenarios)
    - calculation models for avalanche run-out distance (snow- and rock-avalanches)
    - avalanche volume, density and velocity (pressure estimates)

There have been several attempts to formalise this survey process, (Aagard et al., 2001). This reveals itself to be complex when studying the individual aspects.

2.3 Consequences

Avalanches affecting road-users on public highways lead annually to 1 to 2 fatalities in Norway. Moreover, 70 to 80 % of all road-blockages in Norway are caused by avalanches (Public Roads Administration Hordaland, 1995), highlighting, in some areas, a substantial socio-economic challenge. The fact that road-tributary and main arteries are temporarily incapacitated, may lead to relatively serious economic harm, especially where alternative routes are limited. Indirect health hazards can occur as a result of road-blockage, e.g. when the passage of emergency-vehicles is hindered. The threat of avalanche gives rise also to mental strain, e.g. for those who must commute or transport their children through avalanche-threatened areas.

The consequences of an avalanche hitting a car depend on several factors. The avalanche volume, density and velocity are important measurements in determining the degree of severity. However, only a minor direct influence of the avalanche may cause a driver to lose control of the vehicle. The conditions beyond the roadway may be significant in such cases and it is not unusual in western and northern Norway for avalanche prone roads to run adjacent to fjords.

General avalanche statistics from Switzerland (Tschirky et al., 2000) suggests that the number of fatalities among those completely buried under avalanche snow amounts to about 50 %. Swiss statistics specifically concerning the fatality rate in vehicles involved in avalanches, gives 18% fatalities and 31% injuries (Wilhelm, 1997). In Norway, good data on death rates are lacking, but it seems reasonable to assume that likelihood of death or disablement may be higher than in a Central European country because of topographic characteristics, more remote areas and longer rescue times. Thus, in some examples below we assume a ratio of 2/5 for the death rate.

When several individuals are affected by the same accident, this accident will normally be regarded as more serious than the same number of people being affected by separate accidents. This is due to the "aversion factor". Aversion depends upon peoples' perception of the severity of an accident, cf. Section 4.2.2.

The consequence of a fatality can also be quantified from the cost to society, ("value of life"). This is, however, subject to some controversy. The subject is briefly discussed in Section 4.6.

2.4 Probability of encounter between avalanche and vehicle

The probability of a vehicle being hit by an avalanche is the product of a) the probability of an avalanche release, b) the probability of the avalanche reaching the roadway; and c) the probability that the avalanche reaching the roadway hits a vehicle.

2.4.1 Probability of an avalanche release

The calculation of a realistic probability for future avalanches is, without doubt, the most time-consuming part of the entire risk-analysis. The calculations make large use of non-quantifiable criteria, (i.e. discretion), in addition to meteorological and topographic conditions. The stability of snow-cover depends naturally on snow-pack structure, whilst stability on a mountainside depends also on the geology.

Some methods are, however, established, at least for some avalanche types. For snow-avalanches, the probability of release can, in principle, be calculated using:

- Mechanical/probabilistic models (snow-pack structure is described by means of physical variables with distribution functions providing the probability of parameter values); or
- Statistical models (based on meteorological data and/or historical snow-avalanche observations)

Both these methods are described by Harbitz et al. (2001), although such models do have their limitations (Kristensen et al., 2000).

As already mentioned, it is disputable whether it is useful to examine frequency with respect to rock-falls and rockslides. These phenomena differ from snow-avalanches, since they are not closely associated with seasonal variations. For some large mountain slopes, rock-fall activity can be somewhat regular from year to year, but in others, it represents the culmination of gradually increasing activity that initiates a larger rockslide. In such cases, only a rock stability evaluation can give some indication of the probability of release.

2.4.2 Probability of an avalanche reaching the roadway

If an avalanche is released at some point above the roadway, the next question must be: how great is the probability of it reaching the roadway. This question also is difficult to answer; however, there are some established models for calculation of run-out distance. They can be categorised as either:

- Dynamic/probabilistic models (avalanche movement is described by means of physical variables with distribution functions to give probability for parameter values); or
- Statistical/topographic models (run-out distance for a given probability is calculated from a basis of recorded known avalanche run-outs).

2.4.3 Probability that an avalanche reaching the roadway hits a vehicle

Certain permanent installations, e.g. a house or a road body, are permanently exposed to the possibility of avalanche danger. This is not the case, however, for mobile objects, such as cars. Here it is necessary to consider the probability of a vehicle being in the path of the avalanche, as the avalanche reaches the road. The probability for this to happen depends on the avalanche frequency, the width of the avalanche and on the time vehicles find themselves within the avalanche area. This in turn depends on the traffic-volume; speed and stopping-distance.

3 SCENARIOS

This section presents calculation examples regarding collision between avalanches and random or particular vehicles in movement, as well as collision between avalanches and stationary vehicles. The calculations are more thoroughly explained by NGI (2003). Where no references are made, the parameter values serve only as examples. The calculations ignore possible safety measures.

3.1 Collision between avalanche and random vehicles in movement

Example 1: Infrequent snow-avalanche over road with relatively heavy-traffic
The situation is as illustrated in Figure 1. Assume that $N_d = 1200$ cars per day are passing with speed v = 40 km/hr, or 11 m/s. This represents a stopping distance of l = 25 m which comes in addition to the snow-avalanche width of $S = 55$ m. The stopping distance has to be added to account for the vehicles that are not able to stop before they run into the flowing avalanche. The average

snow-avalanche-frequency per year is taken as being one snow-avalanche every other year, i.e. number of snow-avalanches per year is $f = 0.5$.

The annual probability of a car being hit is given by $p = \frac{N_d \cdot (S + l) \cdot f}{v \cdot 3600 \cdot 24}$

The average number of cars hit by avalanche per year is now 0.05, or one car every 20 years on average.

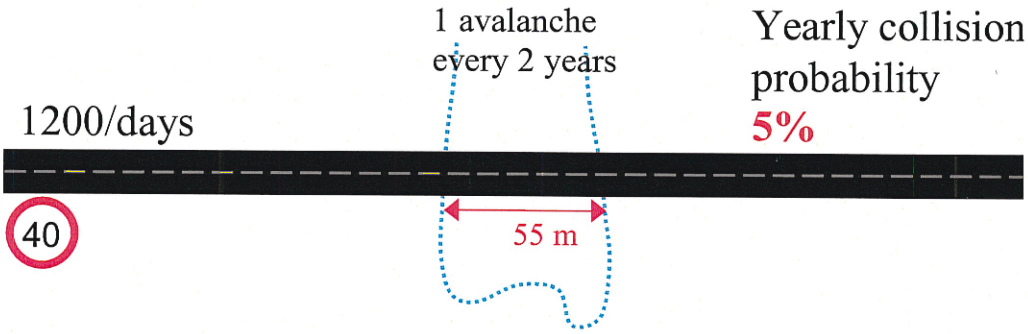


Figure 1: Simplified view of probability of vehicle being hit by infrequent snow-avalanche on a heavily-trafficked road.

The annual probability of a particular car being hit is 0.05/1200 = 0.00004, see section 3.2 about individual probability.

Example 2: Frequent snow-avalanche over road with light-traffic
The situation is as illustrated in Figure 2. Assume the passage of $N_d = 80$ cars per day with a speed of $v = 40$ km/hr, or 11 m/s. A stopping distance of $l = 25$ m comes in addition to the snow-avalanche width of $S = 100$ m. The average snow-avalanche frequency per year is taken as being five per year, i.e. $f = 5$. The average number of cars per year hit by snow-avalanche is again shown to be 0.05 or one car per 20 years on average.

The annual probability of a particular car being hit is now 0.05/80 = 0.0006, see section 3.2 about individual probability. Notice how despite the annual probability of a car being hit by snow-avalanche is the same in the two above examples – the individual probability is far greater in the latter example.

Consider now seasonal variations where snow-avalanche danger may only be present for half the year. The correct approach would be to examine only the exposure times for the period of snow-avalanche danger. If car traffic is constant all year we will, however, arrive at the same result as in Example 1, because total exposure time (numerator) and the period in question (denominator) remain proportional to the period under consideration, (365 days in Example 1). If car traffic differs significantly in snow-avalanche prone periods in contrast to the rest of the year, applying annual car statistics could lead to considerable calculation error, see Example 4.

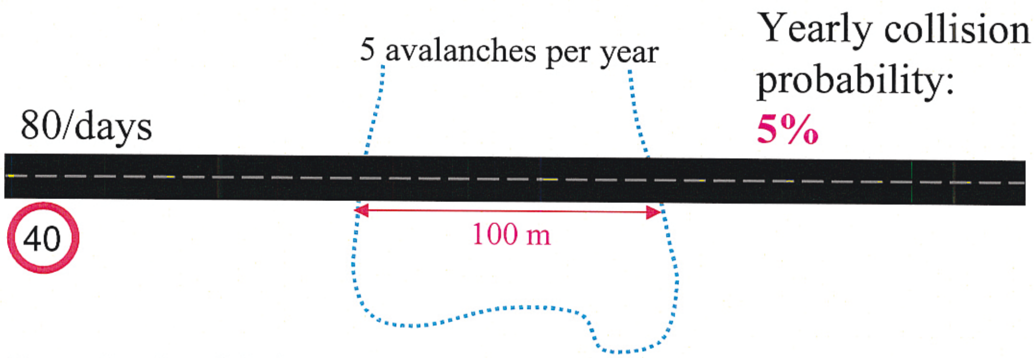


Figure 2: Simplified view of probability of vehicle being hit by frequent snow-avalanche on a lightly-trafficked road..

Example 3: Risk – general example

B = occasional ('average-') car is hit
S = avalanche width (m)
l = stopping-distance (m)
v = car speed (m/s)
f = annual number of avalanches
T_r = average number of years between avalanches that traverse roads = $1/f$
T_e = exposure time (s) (per passing) = $(S+l)/v$
T_0 = reference time (days) (e.g. in the course of a year, or that part of the year when avalanches are possible)
T_s = reference time (hours) with given avalanche danger
N_d = average number of car passes per day
N_m = average number of cars hit by avalanche per year
N_i = number of passings for a particular car per T_0
N_s = number of passings for a particular car per T_s
p = probability of an average car being hit by avalanche
p_s = probability of an avalanche reaching the roadway in the course of T_s (degree of avalanche danger)
R = risk
K = average consequence of a car hit by avalanche

Average number of cars hit by avalanche per year, will now be:

$$N_m = (N_d \cdot T_e \cdot T_0 \cdot f) \ / \ (24 \cdot 3600 \cdot T_0) = N_d \cdot T_e \cdot f \ / \ 86400$$

Notice that T_0 cancels out from the formula above.

When we have determined N_m, the risk will be:

$$R = N_m \cdot K$$

If we look at death risk per year, K would represent the average number of passengers per car multiplied by average number of those passengers who die when the car is hit by an avalanche.

Example 4: Death-risk in car.
An area is said to be snow-avalanche prone over 100 days. Assume the passage of 1200 cars per day with an average number of 2 passengers per car, and that on average 2 of 5 passengers die if the car is hit by avalanche, (i.e. that on average $2 \cdot 2/5 = 0.8$ passengers per car die when the car is hit by avalanche). Assume further that on average there is a road-breaching avalanche every 5 years with an average avalanche width (including stopping-distance) of 125 m, and with all cars maintaining a speed of 50 km/h. What is the yearly death-risk due to avalanche?

The numbers provided correspond to $N_d = 1200$, $f = 1/5$, $T_e = 9$ s. The number of cars hit by avalanche per year, therefore, is on average

$$N_m = 1200 \cdot 9/(86400 \cdot 5) = 0.025$$

Further, we get a yearly death-risk of $0.025 \cdot 0.8 = 0.02$, i.e. that on average one passenger will die per 50 years.

For average-type considerations such as expected fatalities per year, it is only the number of passengers per year which is significant. How even or uneven the traffic is, can however, have great significance for when accidents occur and also for their individual consequences.

Assume a case where there is only traffic during the early morning and late afternoon, (representing traffic to and from work). If the car density is so small that the distance between cars is greater than avalanche width; the accident *portrayal* will be identical with the case of even traffic, (with the same number of passings), for the whole day. If however, there are traffic queues each morning and afternoon with more cars within a length corresponding to an avalanche width (but still the same total amount of car passings per day); the number of accidents will be fewer (fraction of time with cars in the avalanche path is reduced), but will have greater consequences (more cars involved), in every accident.

If traffic is shifted such that there are more cars passings in the non-avalanche period, i.e. no snow-cover, the situation becomes changed. Assume for example that there are on average N_d car passings per day on a yearly basis, while traffic is k times as much when it is snow-free. The number of car passings per day in an avalanche prone period will be:

$$\frac{N_d \cdot 365}{T_0 + k(365 - T_0)}.$$

Using data from the previous example and assuming the avalanche-prone period to be $T_0 = 100$ days and that there are twice as many car passings (k = 2) when it is snow-free; we get 695 passings per day when there may be an avalanche. The yearly risk of death declines therefore with a factor of 695/1200 to approximately 0.012.

3.2 Collision between avalanche and particular vehicle in movement

Here we consider the individual probability, i.e. the probability of a particular vehicle being hit. This can be a relevant consideration in the case of, for example, maintenance crews or school buses.

The individual probability of a particular vehicle being hit in the course of a year is:

$$p(B) = \frac{N_i \cdot T_e \cdot f}{T_0 \cdot 86400}.$$

The individual probability of a particular vehicle being hit in the course of a given avalanche-risk situation is, however:

$$p(B) = \frac{N_s \cdot T_e \cdot p_s}{T_s \cdot 3600}$$

Example 5: Individual probability of a car being hit in the course of a "snow-avalanche day"
Assume firstly that there is a high snow-avalanche risk, i.e. a period of $T_s = 12$ hours with more than 50 % probability of snow-avalanche. Assume also that the car speed is $v = 50$ km/h or barely 14 m/s, that snow-avalanche width is S = 100 m and that stopping-length is $l = 25$ m. The car passes $N_s = 1$ time, using 9 s to get across.

The individual probability of a particular car being hit in the course of $T_s = 12$ hours with snow-avalanche probability $p_s = 0.5$, is then 0.0001. This means that a particular car passes on average 10,000 times for each time it is hit.

Examine now the probability of a snow-plough being hit in which it passes the snow-avalanche area $N_s = 10$ times in the snow-avalanche-prone period. The snow-plough passes with a speed of $v = 40$ km/hr or 11 m/s. The situation is otherwise as above. This gives an individual probability of the snow-plough being hit as 0.0013.

3.3 Probability of a stationary vehicle being hit by avalanche

We will now examine the situation of a car stuck in a place prone to avalanche. This is a typical situation which arises when the roadway is initially blocked by an avalanche resulting in a queue of cars which is thereafter hit by a "neighbouring-avalanche" (i.e. a situation where there has been in advance a "main-avalanche" in a nearby avalanche path). Neighbouring-avalanches have shown themselves to cause several accidents.

It is evident that the probability of a neighbour-avalanche in the course of, for example, the next two hours is far greater than in any other period. Fitzharris and Owens (1980) estimate this conditional probability to be about 15 %.

This number may arise from a situation where the starting point is high snow-avalanche risk (i.e. a period of 12 hours with a snow-avalanche risk exceeding 50 %). After a confirmed snow-avalanche the probability of a nearby snow-avalanche is increased, for example to 90 %. If the first snow-avalanche has blocked the roadway and cars are held stationary and exposed to a neighbour snow-avalanche for 2 hours, the probability of these being hit by the neighbour snow-avalanche will be $0.9 \cdot 2/12 = 0.15$. The figure seems to depend greatly upon the time-interval used. The degree of dependence to neighbour-avalanches relates also to its *exposition* and height above sea-level, etc. in relation to the main-avalanche. The uncertainty in this dependence should be reduced by closer studies.

Hence, if we want to quantify e.g. the fatality risk related to a possible neighbour avalanche, this is a far more complicated situation than in the previous examples. The probability of neighbour avalanche release decreases with time. In addition, the risk is different for a moving car approaching the cars being stuck already, compared to the risk for the cars being blocked. As time goes by, there will also be a trade off between the decreasing avalanche probability and the steadily increasing number of cars being exposed to a neighbour avalanche. A more complex model is therefore needed.

3.3.1 Vehicle and neighbour snow-avalanche – more complex analysis

Let b signify the length of the stretch of road where there may be a snow-avalanche. We will also assume that the road location where a snow-avalanche will occur is uniformly spread. We further assume that the position of the neighbour snow-avalanche, (snow-avalanche 2 along the same stretch of road and released under the same circumstances which released snow-avalanche 1), is uniformly distributed and independent of the position of snow-avalanche 1. It may be of interest to note that the probability-density of the distance, d, between two subsequent snow-avalanches, will follow a triangle distribution with greatest probability of co-positioning and linear reductional probability-density:

$$f_s(d) = (2/b)(1 - d/b), \quad 0 \le d \le b$$

Let x_1 signify the position of snow-avalanche 1, x_2 the position of the neighbour snow-avalanche and let increasing x-values be synonymous with movement to the right. If, for a given x_1, the neighbour snow-avalanche releases by $x_2 > x_1$, this will give a prone neighbour snow-avalanche stretch of $b' = b - x_1$. In this case only the cars to the right of x_1 are exposed. Generally, we observe that the area vulnerable to neighbour snow-avalanche is stochastic, (chance-dependent on where snow-avalanche 1 releases), and uniformly spread.

Further, we shall assume that the probability of neighbour snow-avalanche declines (exponentially) with time, t, signified by density.

$$f_S(t) = \frac{1}{\tau}\exp(-t/\tau), \quad 0 \le t \le \infty$$

Note that $f_s(t)$ is a probability-density function with integral equal to 1, indicating how **relative probability** for neighbour snow-avalanche varies over time. The parameter τ is in the same size range but somewhat less than the time one suspects neighbour snow-avalanche, e.g. 2 hours. We let p_2 signify the probability of neighbour snow-avalanche release; the suggested value above being $p_2 = 0.15$.

Car traffic is assumed to move normally before it stops-up due to snow-avalanche 1. As a simplification, we choose to ignore the gradual slowing down of car speed. Let x signify the length of a car queue facing the snow-avalanche. We assume that x increases proportionally with time, (steady-traffic), and with traffic-density N_d, (number of car passings per time unit). If every car in the queue takes up a length L, we then get:

$$x(t) = N_d \cdot L \cdot t$$

Next, we will distinguish between the risk attached to cars in movement, with speed v, and cars which remain stationary due to the queue facing snow-avalanche 1. These two situations will be referred to respectively as "*dyn*", for dynamic and "*sta*", for stationary. For simplicity, we initially let the prone neighbour snow-avalanche stretch, b', be known, i.e. that x_1 is known. The localisation of the neighbour snow-avalanche will then be uniformly, (and not triangularly), spread over $[x_1, b]$, (because there is only one uniformly spread variable, x_2, remaining after snow-avalanche 1 has released, whereas previously there were two uniformly spread variables whose average gives a triangular spread as described above). Also for simplicity, we make $x_1 = 0$. Let us also begin by viewing consequence, *K*, in the form of number of cars hit by snow-avalanche. We then arrive at:

$$K_{sta} = S/L = n_{sta}\,, \quad K_{dyn} = n_{dyn}$$

where *n* is the number of cars within a stretch of road with length equal to the neighbour snow-avalanche's width, *S*. n_{dyn} will be proportional with the traffic density N_d, (number of car passings per time unit), and will as a rule be considerably less than n_{sta}. The corresponding **risk-densities** (risk per time unit), are:

$$f_{R,sta}(t \mid b') = \begin{cases} p_2 f_s(t) \cdot \dfrac{x(t)}{b'} \cdot (S/L), & x < b' \\ p_2 f_s(t) \cdot (S/L), & x > b' \end{cases}$$

$$f_{R,dyn}(t \mid b') = \begin{cases} p_2 f_s(t) \cdot \dfrac{b'-x(t)}{b'} \cdot n_{dyn} = p_2 f_s(t) \cdot \left(1 - x(t)/b'\right) \cdot n_{dyn}\,, & x < b' \\ 0 & x > b' \end{cases}$$

where $p_2 f_s(t)$ signifies the probability of neighbour snow-avalanche as a function of time, $x(t)$ is the length of the queue and $b'-x(t)$ is the stretch of cars in movement. We deduce the corresponding risks by integrating the densities over the time, *t*. This gives the **conditional risk**:

$$R_{sta} \mid b' = \int_0^\infty f_{R,sta}(t \mid b')dt = p_2 \cdot \left(\frac{N_d \tau}{b'/S}\right) \cdot \left(1 - e^{\frac{b'/L}{N_d \tau}}\right)$$

$$R_{dyn} \mid b' = \int_0^\infty f_{R,dyn}(t \mid b')dt = p_2 \cdot n_{dyn} \left(1 - \frac{N_d \tau}{b'/L}\left(1 - e^{\frac{b'/L}{N_d \tau}}\right)\right)$$

These risk expressions are somewhat conservative since we integrate *t* to infinity. This represents, however, a marginal effect.

Note that for a given *b'*, the probability of a neighbour snow-avalanche releasing within *b'*, given that a neighbour snow-avalanche releases, is equal to *b'/b*. When we integrate out *b'* to get the unconditional risk, we must accordingly multiply with this probability. Note also, that we have only considered neighbour snow-avalanche to the right of snow-avalanche 1. In principle, we should also have included the possibility of a snow-avalanche to the left, ("doubling the risk" since the integration of neighbour snow-avalanche to the right *or* to the left gives the same result based on symmetry). This is however, balanced by the fact that it is only the cars on the one side of snow-avalanche 1 which are hit by the neighbour snow-avalanche, ("halving the risk"). It is sufficient therefore, to integrate out b' for the neighbour snow-avalanche to the right. This gives:

$$R_{sta} = \frac{1}{b}\int_0^b \left(\frac{b'}{b}\right) \cdot R_{sta} \mid b' db' = p_2 \cdot \left(\frac{N_d \tau}{b/L}\right) \cdot n_{sta} \cdot \left(1 - \left(\frac{N_d \tau}{b/L}\right)\left(1 - e^{-\frac{b/L}{N_d \tau}}\right)\right)$$

$$R_{dyn} = \frac{1}{b}\int_0^b \left(\frac{b'}{b}\right) \cdot R_{dyn} \mid b' db' = p_2 \cdot n_{dyn} \cdot \left(\frac{1}{2} - \left(\frac{N_d \tau}{b/L}\right)\left(1 - \left(\frac{N_d \tau}{b/L}\right)\left(1 - e^{-\frac{b/L}{N_d \tau}}\right)\right)\right)$$

The dimensional expression $c = (b/L)/N_d\tau)$ crops up again and again and we may simplify the expressions to the following:

$$R_{sta} = p_2 \cdot n_{sta} \cdot \frac{1}{c}\left(1 - \frac{1}{c}\left(1 - e^{-c}\right)\right)$$

$$R_{dyn} = p_2 \cdot n_{dyn} \cdot \left(\frac{1}{2} - \frac{1}{c}\left(1 - \frac{1}{c}\left(1 - e^{-c}\right)\right)\right)$$

Both expressions are positive for $c>0$. The total risk will be $R_{tot} = R_{sta} + R_{dyn}$. If $n_{sta} = n_{din}$, we see that $R_{tot} = \frac{1}{2} p_2 n_{sta}$ = constant, independent of c. In practice n_{sta} will be much larger than n_{dyn}. Note also that R_{sta} decreases proportionately to increasing c, for example with declining car traffic N_d.

Example 6: Risk associated with neighbour snow-avalanche
Let $p_2 = 0.1$, $\tau = 1/24$ (1 hour), $b = 3$ km, $L = 7$ m. From before we have $S = 100$ m such that $n_{sta} = 100/7$. Further, $N_d = 1200$/day, $n_{dyn} = T_e N_d/86400 = 1200 \cdot 9/86400 = 0.125$. By using the formuli above we get $c = (b/L)/(N_d\tau) = 8.571$, $R_{sta} = 0.147$ and $R_{dyn} = 0.0050$. Accordingly, we would expect that on average 0.15 cars will be hit by neighbour snow-avalanche every time there is a main snow-avalanche, i.e. on average 1 car per 7 main snow-avalanche releases. With $T_r = 5$, ($f = 1/5$ snow-avalanches per year), this would mean on average 1/7/5 = 0.03 cars per year because of neighbour snow-avalanche, or about as many as are hit by main snow-avalanche, see Example 4.

3.4 Combined probability

If a stretch of road is vulnerable to, for example, both rockfall and snow-avalanche, it is prudent to investigate the possibility of a vehicle being hit by two independent avalanche incidents.

Example 7: Probability of being hit by two independent avalanche incidents
Given the probability of snow-avalanche traversing a roadway to be $a = 1/200$, and a probability of rock fall over a roadway to be $b = 1/50$. The collective probability for an avalanche incident is represented thus:

$$p_1 = a + b - (a \cdot b) = 1 / 200 + 1 / 50 - 1 / 10\,000 = 249 / 10\,000 \approx 1 / 40$$

This may be easier to comprehend by exploring the probability of an avalanche incident not occurring, given as:

$$p_2 = (1 - a)(1 - \mathrm{b}) = 9751 / 10\,000$$

Probability of an incident is then:

$$p_1 = 1 - p_2 = 249 / 10\,000 \approx 1 / 40$$

3.5 Quanitification of uncertainty

Example 8: Quantification of *uncertainty* – use of confidence intervals
Take an area where over an observational period of 30 years, 6 different avalanche incidents have occurred resulting one car being hit each time, and where we wish to estimate a yearly probability of a car being hit by avalanche. We assume that the number of such accidents in the course of 30 years is Poisson-distributed with the unknown parameter λ and estimate $\lambda^* = 6$ accidents per 30 years, (corresponding to an estimate of 0.2 for yearly probability of an accident).

We first find an upper value for *actual* λ such that there is a less than or equal to 5 % chance of observing $\lambda^*_{obs} \leq 6$. We say then that we are 95 % sure of λ not being exceeded, (a 95 % confidence-interval for λ being a somewhat conservative choice). If the actual value were higher, there would be a less than 5 % probability of observing a value as low as $\lambda^*_{obs} = 6$.

We may do this by solving the equation $P(\lambda^* \leq 6 \,|\lambda) = 0.05$ with regard to λ, which must be done numerically: the solution being $\lambda = 11.8$. We are then 95 % sure of the yearly probability of an accident not exceeding $11.8/30 = 0.39$ when 6 cars have been hit in the course of 30 years. If we from other statistics know that there are two fatalities in each accident, (corresponding to 0.8 in Example 4), we arrive at a corresponding limit for yearly death-risk of 0.78, of which we are 95 % sure.

The transition from confidence-interval of an accident to confidence-interval for death-risk may be more closely reasoned thus: Let X_i signify the number of passengers who die in car number i which is taken by avalanche in the course of a known period, n_{yr}. Further, let Y be the number of cars taken by avalanche within this period, i.e. $i = 1,\ldots,Y$. We assume the expected number of fatalities per accident, (E$X_i = \mu$), to be known, (corresponding to the average number of fatalities per accident distributed over a large number of accidents). The observed number of fatalities, N, can now be expressed:

$$N = \sum_{i=1}^{Y} X_i$$

Note that both the X_i values and Y here are stochastic. To find the expectations pertaining to N; we make use of the rule of double-expectation:

$$EN = E_Y\left(E_{N|Y}\left(\sum_{i=1}^{Y} X_i \mid Y \right)\right) = E_Y\left(\sum_{i=1}^{Y} X_i \mid Y \right) = E_Y\left(Y \cdot EX_i\right) = \mu \cdot E_Y Y = \mu \lambda_{yr} n_{yr}$$

where λ_{yr} is the expected number of cars taken by avalanche per year. Since EN is proportional to λ_{yr} with “known” proportional factor μn_{yr}, the transition from a confidence-interval for λ_{yr} to a confidence-interval for yearly death-risk EN/n_{yr} is straightforward as done above : $EN/n_{yr} = \mu\lambda_{yr}$.

The use of confidence intervals for the quantifying of insecurity in relation to avalanche-danger zoning is more comprehensively covered by Harbitz et al. (2001).

4 RISK-MANAGEMENT

Risk-management in this connection covers measures to be initiated in order to either; reduce the probability of avalanche reaching the roadway, (**cause-preventative measures**), or; to limit damage effects in the event of avalanche breaching the roadway, (**consequence-reduction measures**). In addition, laws and regulations can determine the framework for what constitutes an acceptable level of risk. Risk-management also often involves an assessment of benefit value, reliability and priority of measures.

4.1 Measures against avalanche accidents

The **cause-preventative** measures can include measures both in the release zone and in the run-out zone in order to hinder avalanche reaching the roadway.

Avalanche–preventional measures in the starting zone

- Wind fences
- Supporting structures
- Forestation
- Controlled avalanche release, (several small avalanches which do not reach the roadway, in order to avoid a larger avalanche)

Avalanche–preventional measures in the run-out zone

- Tunnel/culvert
- Galleries
- Bridges
- Catching dams
- Braking mounds
- Deflecting dams

The **consequence-reduction** measures chiefly aim at avoidance of exposure of road-users to the danger of avalanche, but rescue services can also reduce consequences in a situation when vehicles have been hit by avalanche. The following measures are often implemented:

- Warnings
- Controlled release of large avalanches
- Area closure in extreme weather conditions
- Protected convoy passage, (can both reduce and increase the consequences)
- Traffic regulation
- Regulation of exposure time or possible stop restriction
- Differentiation of vehicle type (difficult to carry out in practice)
- Rescue services
- Crisis-management plans

4.2 Acceptance criteria

What degree of risk is acceptable? Unfortunately it is difficult to determine a definite degree of risk acceptable to society. To get an idea of what is acceptable; one can take the fatality statistic of traffic accidents in Norway, which stands at approximately 1:10,000 per inhabitant per year, (approximately 400 fatalities per year out of a total population of 4 million). Despite a steady effort to improve traffic safety, it may be said that this risk level is generally accepted.

The authority's answer is based upon a political consensus of ”acceptably safe”. Such estimations are partly reflected in laws and regulations, (e.g. The Plan- and Building Law and The Environment Law). However, accepted risk in law statutes is not always quantified directly, but since it is legal to drive within current speed limits, the statistical risk involved is considered acceptable.

Degree of free choice also influences the perception of risk. If the situation is based on a voluntary activity like mountain-climbing, one accepts a higher risk than one would if the activity is involuntary (i.e. in some way required by society). Jensen and Sande (1973) use a ratio of 1:10 for acceptable-risk level for obligatory vs. voluntary activity. This is assigned to the degree to which we feel in control of the situation.

If one considers the risk of an avalanche encounter while travelling on a public road an obligatory risk and use the ratio 1:10, the individual fatal-risk assigned to avalanche toward car should be about ten times less than the normal fatal-risk in traffic, i.e. 1:100,000 per inhabitant per year, (this corresponds to 40 fatalities due to avalanche hitting vehicles per year). From this we perceive the individual risk to be acceptably low generally, even though it is unacceptably high in certain risky areas.

In addition, the value of human life is important in connection with acceptable risk. This is dealt with in section 4.6.

4.2.1 Laws and regulations

Public authorities have resolved minimum requirements for the safety of buildings in avalanche-prone areas in The Planning and Building Law of 1986 and Building regulation 1987, cited in Enclosure A. The greatest nominal yearly probability permitted for avalanche toward housing is set at 10^{-3}, (average recurrence period 1000 years). This requirement applies to all types of buildings where people stay for lengthy periods during the winter.

Similar requirements for building-sites or maintenance of existing roads do not exist. Regulations of the Work Environment Law; resolution No.299, “Snow-avalanche danger at residential and building sites” have the following general requirements

1. In those cases where professional judgement during the planning phase shows risk of avalanche within the building area; the avalanche expert, by field investigation, will estimate which safety and measures of preparedness it may be necessary to initiate. It shall also be decided which instructions must be followed in avalanche danger situations.
2. Snow clearing in avalanche risk situations is not allowed. Snow-clearing crews must have access to radiotelephones or other proven communications equipment.

The Work Environment Law sets, therefore, stringent demands as to when construction or maintenance work can be done in avalanche danger situations. Safety demands can be met by frequent road-closure or by physically securing the roadway. It is then a question for society to decide which way roadways are to be secured against avalanche.

4.2.2 Aversion-factor

Different types of accidents are perceived differently among the public and media. A single death due to a fire- or road-accident receives less attention than a death due to an avalanche-accident. In general, accidents caused by natural phenomena seem to attract more attention.

Another aspect is that despite the fact that *many* accidents with small consequences quantitatively represent the same risk to society as the *rare* accident with large consequences – it is the latter that is deemed worst (NGI, 1996). This has to do with the public perception of the seriousness of an accident and is referred to as the "aversion" to major accidents. One can therefore reckon with an aversion factor for accidents where several are involved at the same time.

In this context it is interesting to consider the use of "protected convoy passages" on an avalanche exposed road stretch, as opposed to allowing free single car passages. Consider that a column of 20 cars takes 2 minutes to pass through an avalanche risk area in a situation where there is a 50 % chance of avalanche over 12 hours. The probability of the column being hit in this case is 0.0014. Conversely, the probability of one of the single cars being hit is 20 times higher, i.e. 0.028. The consequence however, is 20 times greater if the column is hit, such that the risk is the same in both cases.

However, the aversion factor is far greater if a large column is hit. Wilhelm (1997) makes the point that the aversion factor, σ, varies according to scale of damage, A, such that $\sigma = 0.25$ A. On this basis, an accident where a column is hit by avalanche and A = 16 deaths, is seen as 4 times worse than 16 different accidents where a person dies as a result of cars being allowed singly through the avalanche area. Conversely, an accident where a column hit by avalanche and A = 2 deaths; is seen as half as bad as two accidents where one person dies as a result of cars being allowed singly through the avalanche area.

If the expression for aversion factor is correct, one single accident with four fatalities is equated with four different accidents with one fatality each. The best alternative between protected convoy passage or free passage in a given situation will also depend on, amongst other factors, traffic-density and avalanche width.

4.3 Prioritizing of road communication

Different road connections have different demands for avalanche safety and regularity and the road network is also classified according to this classification. In planning new communications or upgrading older ones, there is sometimes a need to compare different alternatives.

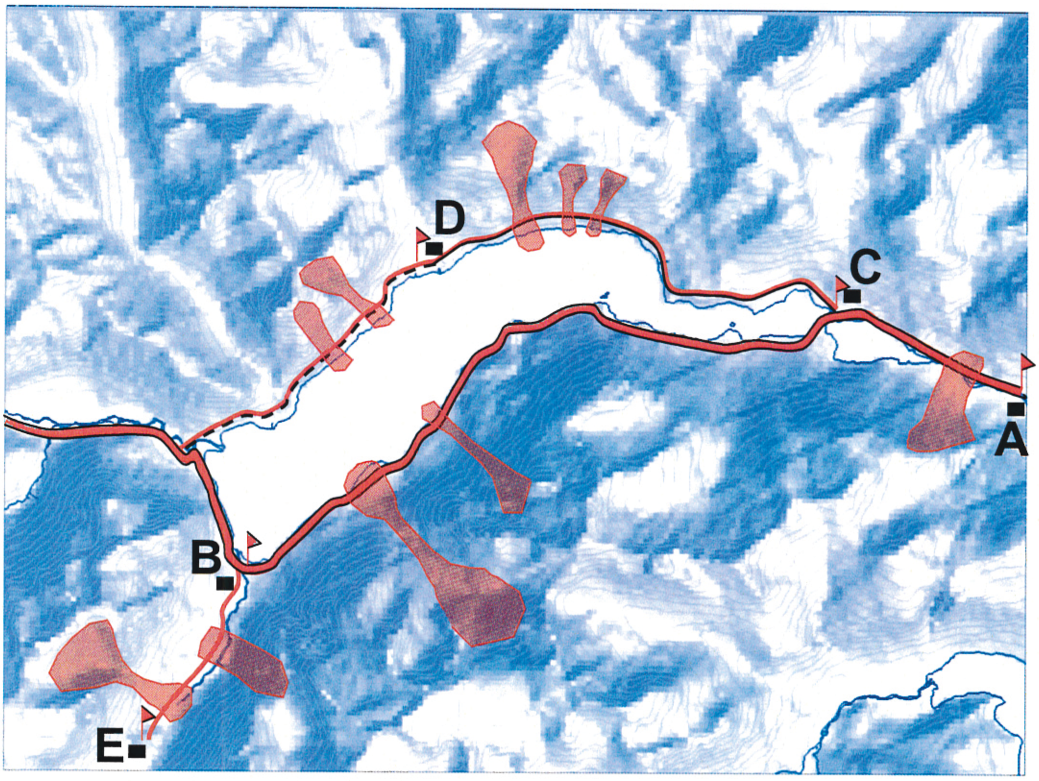


Figure 3: Example of avalanche-prone main highway on south bank of lake with possibility of diversion via by-road on north bank. Important centres are marked by black rectangles and avalanche paths in red.

A simplified way of doing this can be to divide stretches of road according to diversion possibilities and "importance of regularity". In this concept, there may be an estimate of the social disruption a closure would mean in relation to road-type, traffic-density, traffic-type (private, public, commercial, school bus, ambulance) and which centres of functional importance are connected.

Figure 3 shows a situation where weighting of such characteristics can be applied. The diversion possibility in the example reflects the dependence on probability of avalanche in the different avalanche paths. One must normally allow for a relatively high dependence between avalanches which have starting zones at the same height and aspect, see discussion in section 3.3 concerning neighbour-avalanches.

The importance of regularity and diversion possibilities can either be weighted on a sliding scale from 0-1 (Table 1) or divided into classes for use in a matrix (Table 2). In Table 1 the need for mitigation appears as the product of the importance of regularity and the improbability of a diversion. In Table 2 one has defined a limit for actions in relation to the classes in the matrix.

The relative risk to road users on the different alternative routes can be compared using the calculation methods for encounter probability as examined in the previous section. Such an analysis may of course show that taking a long route with relatively infrequent avalanches may lead to a higher risk taking the short route through a more avalanche-prone area. The complicating factor in this analysis is that it requires an estimate of the dependence of avalanche releases along the different routes.

Table 1: Example of emphasis-weighting.

Stretch of road	Road-type	Importance of regularity	Improbability of diversion possibility	Need for action
A — C	Main highway	1	0.9	0.9
B — E	By-way	0.5	1	0.5
C — B	Main highway	1	0.3	0.3
D — B	By-way	0.2	0.8	0.27
C — D	By-way	0.3	0.8	0.24

Table 2: Example of matrix and classification. Letters refer to locations in Figure 3. The shaded blocks define where actions should be made.

	Probability of diversion possibility (classes)			
Importance	4	3	2	1
4	C-B			A-C
3				
2			C-D	B-E
1			D-B	

4.4 Prioritizing measures within a stretch of road

4.4.1 Use of unit-lengths for quantifying avalanche-frequency

In some cases of high variation in avalanche-frequency or avalanche-probability, there may be a need to examine closer the conditions along a stretch of road. By subdividing the road into unit-lengths it is possible to show variations in, for instance the avalanche frequency and the avalanche load, in more detail along an avalanche-prone stretch, see Figure 4. Segment length can be determined according to what is appropriate in each case, but segments can be as small as 10 m of road length. This forms a basis for new cost/benefit analyses and decisions about which parts of a prioritised stretch of road should be mitigated. Unit-lengths are particularly useful when several avalanche types are to be examined together. Use of unit-lengths is further detailed by NGI (1990).

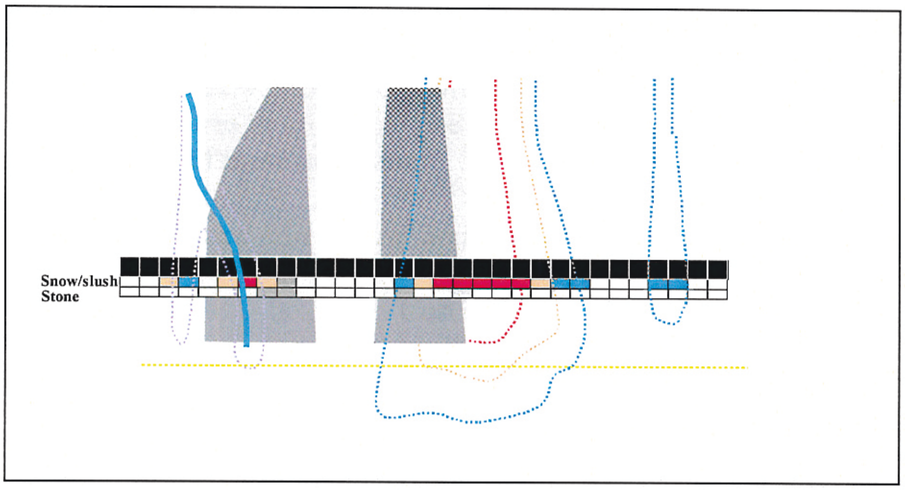


Figure 4: Example of stretch of road affected by several different types of avalanche of differing frequency. Colour coding can be used to indicate avalanche types, frequencies or impact pressures as needed.

4.4.2 Use of weighting-analysis in choice of securing-type

When a stretch has been chosen for implementing measures, a so-called weighted rate method may be useful in determining type of measure and the benefit. This has been suggested as the preferred method by the Public Roads Administration (1993). In short, a weighted rate method explores benefits for each factor, e.g. children's safety or regularity of communications is afforded a graded value, which is derived from the product of two numbers. The first weighted-number indicates the importance of each factor and is distributed such that their sum equals 100. When a factor has twice the weighted-number of another; its higher rating indicates twice the significance of the other. The choice of the first weighted-number reflects the preference of the analyst, for example in the pursuit of safety in contrast to regularity. However, these preferences can, of course, be substantiated by more complex socio-economic analyses.

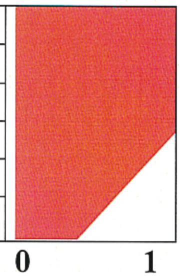
The other weighted-number represents the relative improvement compared to existing conditions for each factor. If, for example, road-closure time for long-distance traffic is reduced by 60 %, the relative improvement will be 0.6, and if the first weighted-number of this factor is 30 – the resulting value will be 18.

The sum of all values produces the total beneficiary effect of a measure. When this is divided by the costs, one arrives at a cost/benefit equation indicating the recommended alternative.

4.5 Residual risk and reliability

Residual risk is the risk remaining after measures, (cause-preventative and consequence-reduction), are effected. Different measures have different effects, something that can be quantified as a reduction of probability and consequence. To arrive at these values, one is often advised to analyse the reliability of the securing-measures in question. The table below illustrates an estimate of costs and reliability of these measures.

Table 3: Estimated cost and reliability of different securing-measures

Measure	Cost (mill. NOK/100 m road)	Reliability
Galleries	7-10*	
Tunnel	3-5*	
Support structures	5-10*	
Catching-/deflecting dams	0.5-1*	
Warning/blasting	0.3 per year	
Warning/closure	0.2 per year	

* Maintenance costs in addition

Quantifying reliability can be achieved in several ways. A simple method of doing this is to view the reliability of all links in a process and place them in an incident- or fault tree analysis, see Figure 5.

4.6 The value of human life

Economic loss due to material damage and fatality will often form part of consequence-assessment, acceptable-risk and choice of safety measure. Some cases use a value rating of human life. The idea is that such a value may be arrived at from society's willingness to invest in life-saving operations, safety measures, rescue services and so on. Society is willing to invest in saving life but funds are usually limited in for example; health services, transport-communication and social services. In a report by the Transport-Economic Institute (Elvik, 1993), the accident costs for society per traffic fatality are calculated to be NOK 15.7 mill. In Iceland and Switzerland, the corresponding figure is NOK 5.5 mill., whilst the figure in England and Austria is NOK 6 mill., (NGI, 1996). In Switzerland it is estimated that society is willing to use approximately NOK 25-50 mill. to prevent a fatal accident, (Johanneson et al., 1996). Research into factual conditions show that the investment for saving a

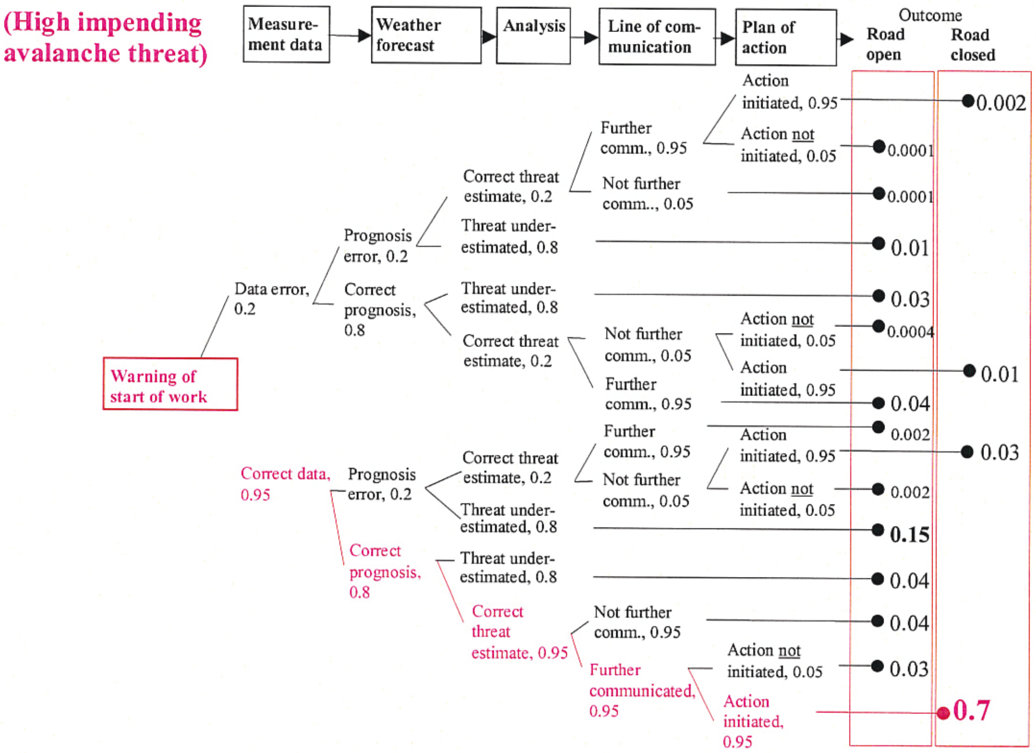


Figure 5: Fault tree analysis for a warning service that should close a road when the probability of avalanche exceeds a certain value. In this example, the analysis indicates that the reliability f such a procedure is about 70 %.

life in the USA can vary from USD 1,000 in the health service to USD 100,000,000 in the nuclear power industry. Thus indicating that estimation, (and law statutes), for saving life can be highly irrational.

This method of calculating the value of human life is therefore both controversial and unclear. There is difference between using money to save life and using resources to prevent the loss of life. The latter case deals with hindrance of “future statistical fatality”, something other than an identified individual death.

In many cases it is unnecessary to place an absolute value on saved lives, since the use of relative values (ratios) work well for different alternatives. Is alternative A better or worse than alternative B with respect to the cost of hindering “future statistical fatality”?

If investments in safety with a limited economic ceiling are to be defended, it is however necessary to make cost/benefit estimates to optimise the reduction in risk with the resources available. In the some of the oil industry the value of statistically saved lives is connected to the level of risk. If an activity implies a yearly fatality probability of, say, 1/1000 (high-risk activity), measures <u>must</u> be initiated irrespective of cost or, alternatively, the activity must suspended. When the yearly fatality probability is reduced to below 1/1000, it must be reduced further to 1/100,000. In the span between these risk-levels, investments will gradually decrease. When risk is high, (close to 1/1000), the cost ceiling is put at, for example, NOK 20 mill. per statistically saved life. Together with decreasing fatality probability, the investments decrease towards the point where probability approaches 1/100,000, something that can be considered an activity with moderate risk, but where limited measures still may be argued for.

5 SUGGESTIONS FOR FURTHER STUDY

The development of procedural descriptions for identifying, mapping and calculating avalanche probability is important for making quantitative risk analyses and decision making tools. In addition, more data is needed to improve the vulnerability part of risk assessment concerning vehicle/avalanche encounters. A further study of road-traffic and avalanches should, in our opinion, address one or more specific transport corridors in an avalanche-threatened region and this work should preferably be carried out in co-operation with the road authorities.

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