STATEWIDE APPLICATION OF THE AVALANCHE HAZARD INDEX

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ABSTRACT: The Avalanche Hazard Index (AHI) (Schaerer 1989, Hendrikx and Owens 2008) has been a useful tool for expressing avalanche risk to highways and railroads for over 30 years. During this time, the AHI method has been applied to many North American and other international transportation corridors. The use of standardized AHI inputs allows for direct comparisons between programmatic risk reduction approaches and has helped guide program managers to make appropriate risk reductions on a broad basis. Recent work has identified the need to update input parameters with new risk findings and to allow for improved comparison of risk reduction approaches on a path-by-path basis.

In this paper, we discuss these approaches for the AHI as used in a recent statewide analysis of the State of Alaska highway system. In total, our analysis in Alaska considered 16 state highways, with 292 avalanche paths and 265 miles of avalanche-vulnerable roadway.

The impetus for this project was the need to understand and quantify the transition from predominantly artillery-based risk reduction methods to other approaches in the future, for example, Remote Avalanche Control Systems (RACS). Important input variables were examined in light of recent findings, such as waiting traffic variables, including secondary encounter probability. The result of these changes to input variables, which we term the “Consultants’ Best Estimate” (CBE), needs to be considered uniformly across an analysis. It allows for direct comparisons within a particular analysis and, in many cases, is expected to describe modern risk values more accurately.

KEYWORDS: Avalanche Hazard Index (AHI), Consultants’ Best Estimate (CBE) Highway Avalanche Risk, Remote Avalanche Control Systems (RACS), Advanced Forecasting Technology (AFT)

1. INTRODUCTION

The Avalanche Hazard Index (AHI), described by Schaerer (1989), has been a useful tool for quantifying avalanche risk to highways and railroads worldwide. The work completed by the authors on a statewide AHI project in Alaska used both a standard and an expert-guided approach for input parameters, building on previous work for a more comprehensive and accurate assessment of risk values.

The development of templated AHI-based risk equations allows users to make easy changes to risk index values as more information becomes available. It also allows agency experts to run risk-reduction scenarios to determine appropriate actions and analyze risk-based cost/benefit trade-offs. In total, our analysis in Alaska considered 16 state highways, with 292 avalanche paths and 265 miles of avalanche-vulnerable roadway. This paper presents some of the considerations, challenges, and findings from our Alaska statewide AHI work.

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2. BACKGROUND

The AHI considers both moving and waiting traffic, and is a function of:

- The size and type of avalanche,
- frequency of avalanche occurrences,
- number of avalanche paths and the distance between them,
- total length of highway exposed,
- traffic volume and speed, and
- type of vehicle.

The following updated equation (Schaerer, 1989; Hendrikx and Owens, 2008) is used to calculate AHI:

$$AHI = \sum_{i=1}^{i=n} \sum_{j=1}^{j=5} W_j (P_{mij} + P_{wij}) \tag{1}$$

where:

W_j = weighting for avalanche type, j

Pmij = encounter probability for moving vehicles to be hit by an avalanche in path i of weighted size j

Pwij = encounter probability for waiting vehicles to be hit by an avalanche in path i of weighted size j

This paper focuses primarily on adjustments to Wj and Pw factors as part of the Consultants' Best Estimate (CBE) method. Standard or default values for Wj and Pw were recommended by Schaerer (1989) and have been widely used for most studies since that time. We refer to these AHI calculations as the "standard" or "standardized" approach.

3. METHODS

3.1 Weighting Factor, Wj

The weighting factors are relative and based on an average of the impact forces and the costs of losses on a vehicle for each avalanche type. The impact force on a vehicle, Q, is expressed as:

$$\mathbf{Q = (a * b * c * p * (u^2))} \tag{2}$$

Where:

a = average height of impact on a vehicle (m),
b = length of the vehicle exposed (m),
c = a shape factor for hydrodynamic smoothness (unitless)
ρ = average density of the flowing materials (kg/m^3),
u =avalanche velocity (m/s).

The cost factor, C, for the standard AHI, is based on losses for a passenger vehicle, including injuries, loss of life, and other costs valued at $500,000 in 1989 dollars (Schaerer, 1989). Many highways, and certainly railroads, have other types of traffic that must be considered. In addition, the current value of losses varies by jurisdiction and over time. For example, a study for the Colorado Department of Transportation in 2016 assumed a maximum loss of $600,000 based on legislative limits on liability. In Alaska, a maximum loss value of $2,645,000 was used for our work, based on the Alaska Department of Transportation and Public Facilities' (DOT&PF) guidance. These two cost values result in very different weighting factors and AHI values, especially when compared to the original 1989 weighting factor. They also negate direct comparisons between different avalanche jurisdictions and prior AHI assessments. Schaerer (1989) recognized this and presented equations that allow for variable input, but in practice, these modifications are rarely used, and the standard weightings for Wj (ranging from 0-12) are typically applied. The high proportion of truck traffic in Alaska and the need to adapt the AHI to railroads has resulted in a number of unique derived Wj values. In order to differentiate between the standard AHI, which can be used for comparison to other highways using standard inputs, and the different values derived through the use of updated values, we have applied the term "Consultants' Best Estimate" or CBE to the modified method. Both the Standard and CBE approaches are consistent with the original equations provided by Schaerer (1989).

3.2 CBE Wj value

The CBE uses the same equations as the standard AHI for calculating the Pm (moving traffic) and Pw (waiting traffic) encounter probabilities for each class of avalanche, as per Eq. 1.

However, in the CBE, we provided road specific, and path-specific inputs for Ps (probability of an avalanche in path i +/- 1), and Ps' (probability of an avalanche in the same path, and response time in the case of a blocked road, rather than using standard uniform inputs. The CBE also applied updated weighting factors (Wj):

$$\mathbf{Wj = (Q + (C * \lambda) /1000)/20} \tag{3}$$

Where:

Q = the estimated impact force on a vehicle (kN) based on the vehicle type (Eq. 2),

C = the cost (current US dollars) based on the maximum loss value, multiplied by the probability of that loss for each class of avalanche (λ).

Wj was calculated independently for passenger vehicles and trucks, with the CBE method capturing a broader range of vehicle types.

The AHI or CBE does not capture all vehicle types. In particular, we have neglected double trailer trucks in this analysis, which are common on some Alaska highway corridors. The risk for double trailers is higher due to their length and inability to back up on most roads. Oil tankers and hazardous materials also have higher avalanche risks that are not explicitly included in the AHI or CBE. Long trains can be under numerous paths when stopped and become immediately vulnerable to avalanches in adjacent paths, which complicates the risk calculations.

The probability of realizing the projected loss (λ) is important in determining the Wj factor. Originally, losses as high as 80% were assumed for deep avalanches. More recent work (Hamre et al. 2016) has shown that the actual fatality rate for combined avalanche types is closer to 13% per incident in North America, 18% in Europe, and 32% among highway workers charged with plowing roads and cleaning up avalanche debris.

The standard AHI was expanded to include "plunging" avalanches typified by Milford Road avalanches in New Zealand (Hendrikx et al., 2006), and we have added "slush flow" avalanches. Slush flows in Alaska are typically high-speed (up to 30m/s), high-density (up to 900 kg/m3), unique to the Arctic and sub-Arctic, and usually occur during the spring melt season, or following rain-on-snow events. Mid-winter warming conditions may also trigger these events more frequently. Alaska also has many situations where a vehicle might be caught in a "deep" avalanche and carried into adjacent ravines or open water where the probability of realizing the full extent of loss is similar or greater than a "plunging avalanche."

Table 1 illustrates how adjustments to Q, C, and λ result in higher CBE Wj values than the standard AHI weightings.

		Force Values for Calculations >>>>						Cost Calculations>>>>				
Event Type	**Vehicle Class**	a	b	p	c	u	Q	C	λ	Loss Value	CBE Weighting (Wj)	Shaerer Wj (1989)
Slushflow	Cars	1.5	5	950	0.8	30	513	2645	50%	$ 1,323	92	N/A
	Trucks	2	20	950	1	30	3420	2645	50%	$ 1,323	237	N/A
Plunging	Cars	1.5	5	200	0.8	40	192	2645	50%	$ 1,323	76	12
	Trucks	2.5	20	200	1	40	1600	2645	50%	$ 1,323	146	N/A
Deep	Cars	1.5	5	250	0.8	30	135	2645	25%	$ 661	40	10
	Trucks	2.5	20	250	1	30	1125	2645	25%	$ 661	89	N/A
Light	Cars	1.5	5	150	0.8	20	36	2645	5%	$ 132	8	3
	Trucks	2.5	20	150	1	20	300	2645	5%	$ 132	22	N/A
Powder	Cars	1.5	5	100	0.8	10	6	2645	0%	$ -	0	0
	Trucks	2	20	100	1	10	40	2645	0%	$ -	2	N/A

Table 1: Standard AHI weighting values compared to derived modern CBE values

3.3 *Modifications to Encounter Probability (Pm and Pw) for CBE*

Encounter probabilities are calculated the same for either the standard AHI or CBE methods. However, two significant differences are included in the CBE approach. These differences primarily affect the Pw factor and are described below.

Loss Probability from Secondary Event(s)

Recent studies of avalanche fatalities (Hamre et al. 2016) indicate that avalanche events within a two-hour period in the same or adjacent avalanche paths are relatively rare. These parameters (Ps' and Ps, respectively) strongly influence the Pw value. A database with 362 vehicles caught in the 2016 study showed that few repeat or adjacent events occurred after the initial event that blocked the road. The probability of an additional event in a single starting zone path would be very low, with a suggested Ps' value of close to 0 in most cases. The probability for adjacent paths (Ps) is generally accepted to be higher, with a suggested average value for Ps of 0.15. However, Schaerer (1989) noted that Armstrong (1981) used Ps values of 0.03 to 0.05 for Red Mountain Pass in Colorado, which is an order of magnitude lower than Schaerer's (1989) suggested value.

Typically, adjacent paths and those more distal (when considering high traffic roads with longer queues) don't uniformly have the terrain characteristics of the initial path that blocked the road and thus avalanche at different times. Accordingly, applying a standard and fixed Ps value of 0.15 oversimplifies this analysis, and generally leads to unrealistically high AHI estimates. Individual path-to-path estimates should be made, considering all path-to-path probability permutations. This is time-consuming and difficult to apply in practice, and requires excellent records, and when absent expert judgment combined with local knowledge of the avalanche paths and terrain.

The standard AHI method commonly applies universal probabilities of 0.05 (5%) for the same path (Ps') and 0.15 (15%) for the adjacent paths (Ps). For the CBE method, we have reduced the default Ps' and Ps probabilities to 0.01 (1%) and 0.03 (3%) respectively, allowing for custom inputs where these values are better understood. For those paths with a known history of adjacent activity soon after the initial avalanche event, higher values up to 0.05 to 0.1 are given with a high of 0.15. These values were used because they are believed to be more realistic based on the authors' experience, and from discussions with avalanche forecasters at multiple operations across Alaska. The lower Ps and Ps' values have the countering effect of reducing CBE values generated by higher Wj inputs. Because the Pw loss probabilities are applied on a path-by-path basis, the outcomes are not always proportional when comparing the two approaches across different roads. This can be explained by the relative differences in the avalanche types (that govern the Wj inputs) and the waiting traffic component (which are impacted by the Ps and Ps' inputs).

Assigning Risk to a Path - Pw Adj Method

The standard AHI assigns risk to the path that creates the risk, i.e., the path that caused the waiting traffic. For example, if a low-frequency path avalanches, the return period of that path at that given magnitude (i.e., avalanche type) is used to estimate the moving hazard (Pm) for that path. If this same path results in an avalanche that blocks the road, traffic backs up and creates risk in the same (Ps') and adjacent paths (Ps) — which contributes to the waiting hazard (Pw). The waiting hazard is controlled by the probability of further avalanche activity but also the length of time exposed. That additional risk is normally assigned to the path where the initial avalanche occurred instead of the adjacent paths where losses occur. Especially in cases with large traffic volumes or closely spaced paths, where multiple adjacent paths need to be considered, the correct attribution of the risk to the correct paths can have a significant impact on the subsequent analysis and strategy to mitigate risk on a path-by-path basis.

An alternative approach to assigning waiting risk (Pw) has been developed and applied in the state-wide Alaska analysis. Rather than assign Pw to the path that stops traffic, Pw is assigned to the path that impacts the stopped traffic. We have termed this "Pw Adj" in our analysis. This approach does not change the overall Pw value for the road segment. Instead, it assigns the waiting traffic risk to the path responsible for the greatest Pw contributions, irrespective of which path initially stops the traffic. This alternative summation better illustrates where the risk is the highest, where the residual risk is higher, and importantly, the locations where mitigation will be most effective in reducing the AHI. Templates can then be used to more appropriately guide risk reduction efforts.

An example (Figure 1) illustrates where the Pw Adj approach is particularly relevant. Consider the case of an infrequent path (Path A) that is adjacent to a high-frequency path (Path B), where an avalanche in the infrequent path (Return period 100 years) (Path A) leads to a traffic queue extending into the high-frequency path (Return Period 1 to 10 years) (Path B). Using the traditional summation approach, the waiting risk (Pw) caused by Path B is assigned to Path A—with the impact of Path B on the waiting traffic causing the majority of the Pw value.

Using this approach, Path A may be seen as the path with higher risk, even though the actual risk presented to the waiting traffic is generated predominantly by Path B. The Pw Adj approach clearly shows that Path B represents the greatest risk to waiting traffic, and that Path B should be the focus of mitigation efforts.

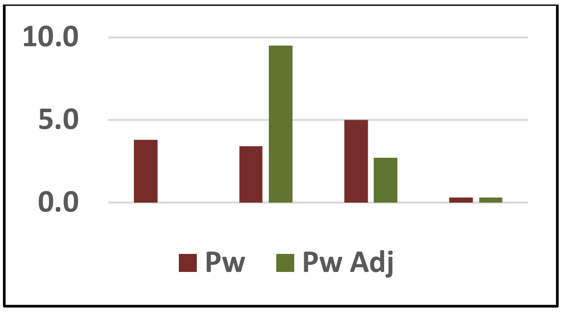

Figure 1: Pw versus Pw Adj

4. RESULTS AND DISCUSSION

4.1 Comparison of Standard AHI to CBE Values

With the increase in weighting values (Wj) partially driven by costs and the decrease in Pw values, mostly driven by lower Ps and Ps' values, and sometimes waiting times, the differences between the standard AHI and CBE are not that substantial overall. Our results suggest that the biggest difference between the standard AHI and CBE is on highways where the biggest risk driver is closely spaced paths that produce high Pw values. This suggests that either the probability of an avalanche in an adjacent path is still too high or that the standard method underestimates the long-term possibility of large losses in cases where a "union of circumstances" can occur over very long temporal intervals. In Table 2, red represents very high hazard, orange is high hazard, and yellow is moderate hazard based on category values commonly used in the avalanche field as defined in "AHI for Colorado Highways" (Mears, 1995). Highways with closely spaced avalanche paths, such as the Seward Highway and Thompson Pass, tend to have CBE values that are higher than the standard AHI values. At lower hazard levels, these differences are not as pronounced.

Highway	AHI	CBE
Seward Highway	212	309
Thompson Pass	136	263
Atigun Pass	98	131
Klondike Hwy.	86	143
Hatcher Pass	61	55
Thane Road	29	37
Pasagashak	16	16
Copper River	11	13

Table 2: Comparison between AHI and CBE Methods

4.2 Other Considerations

The use of "standard" AHI inputs allows for direct comparisons between different roads, and over time when the AHI is recalculated with updated input parameters. It has also helped guide program managers to prioritize and implement appropriate risk reduction measures. Standardized inputs are especially appropriate where there are inadequate detailed records of avalanche occurrence and magnitude to rely on for interpretation of event lengths and depths according to avalanche type. For that reason, in our analysis, standard values are used in most cases and only substituted for data-derived values where there were 20 or more years of accurate records. The lack of avalanche occurrence data and hourly time stamps on data are impediments to providing accurate AHI calculations. This limitation becomes especially evident when considering the waiting traffic component. The use of standard values partially compensates for this. Longer and more reliable records are needed for using actual occurrence data to improve the AHI calculations due to the probability that shorter time period records often omit large and rare events.

In addition to producing user-friendly AHI and CBE templates, we also included an analysis to estimate risk reduction percentages. There is currently limited published work that clearly identifies the level of risk reduction that a program can achieve. Actual risk reduction is somewhat variable both in time, by path, and by program. Table 3 lists risk reduction factors recognizing wide variations in realizing these reduction measure options. The future holds potential for multiple technologies to improve forecasting that can be grouped under the category of Advanced Forecasting Technology (AFT), which includes Infrasound, Radar, GIS, and other integrated systems.

Global Risk Reduction Values Used		
Current forecasting and closures	50%	This assumes some limitations on the closures and using current forecasting techniques.
AFT and closures	65%	Installation of AFT adds an estimated 15% to risk reduction
Active forecasting, RACS, closures	70-85%	Full-time personnel, preventative closures. Installation of RACS or use of artillery on select paths
AFT, RACS, closures	75-90%	Adds AFT but not 15% as RACS decreases benefit. 90% is close to Little Cottonwood Canyon, Utah
AFT, closures, and helicopter mitigation	70-90%	Maximum for an AFT scheme that relies on longer closures and helicopter mitigation. In Milford Road, New Zealand, the figure is 93%.
Permanent Measures	70-95%	Snownets, road relocation, snow sheds, etc. % varies

Table 3: Global Risk Reduction Values

4.3. Conversion from Artillery to RACS

Combining risk scenarios with the capital and operating costs of risk reduction options allows the cost per unit of risk reduction and other cost/benefit analyses to be developed. This allows for objective cost and risk-based decision-making to assist administrators and legislative bodies.

Converting from an artillery-based risk reduction program to other methods requires a comprehensive analysis in most cases. A simple one-to-one shot point replacement is usually prohibitively expensive and is rarely implemented. By applying the new risk equations to a broad area, such as a state, strategies can be developed that counteract the increased risk of losing some artillery shot locations. These strategies may include a calculation that if the risk level is below a given value threshold, it allows the jurisdiction to simply accept the risk of doing nothing, i.e., not implementing any further risk reduction measures. This approach may result in an accident on a long-term basis but is an option that can sometimes be supported by a well-documented analysis and assessment.

Different types of RACS each have strengths and weaknesses that can be accommodated and used to a program's advantage. If only a few shots per year are anticipated, that can skew the advantage to one specific system. If many shots per year are needed, the advantage goes to a different one. Proximity to facilities may be an advantage of a third system. In all cases, an analysis should take these issues into consideration. This can be managed well in a financial versus risk analysis that is based on the output from AHI calculations. Establishing templates for risk calculations makes this process easier, as risk reduction percentages can be applied on the basis of methods used on a path-by-path basis. Since different methods will have different risk reduction values, quick recalculation of the AHI index becomes important for the determination of the best fit for artillery replacement options.

4.3 Worker Safety

In addition to the application of either (or both) the standard AHI or CBE methods, worker safety needs to be considered. Neither formulation of AHI addresses worker safety due to the longer exposure time of workers during higher danger conditions. Hamre et al. (2016) show that fatality rates for highway workers being hit by avalanches are approximately double the level for the general public. The most important time for plow drivers to be on the road is when the highest risk of avalanche activity occurs.

Our Alaska work has shown clearly that it's possible to have a moderate to high AHI rating on a highway that is generated at least partially by the frequent plowing required (e.g., 10 passes per day by a plow operator on a low-volume road), rather than by the risk to the public traffic. In other words, a disproportionate amount of the quantified risk in the AHI accumulates into a small class of workers. Using a Probability of Death for Individuals (PDI) approach (Hendrikx and Owens, 2008) in certain circumstances has shown these values to be one to two orders of magnitude greater than widely acceptable workplace risk levels. The takeaway from this finding is that the issue of worker safety needs to be looked at separately from the calculation of AHI levels.

5. CONCLUSIONS

The avalanche hazard index has been clearly demonstrated as a useful assessment and risk management tool for avalanche-prone roads worldwide. Modified approaches to avalanche hazard evaluations were anticipated in the original AHI work by Shaerer (1989) but have been rarely used in practice. Our statewide work in Alaska has shown the validity of using these methods, with careful consideration given to appropriate input parameters, to obtain a more accurate picture of avalanche risk. This improved understanding of risk then allows for detailed planning of avalanche risk reduction at road and statewide levels to optimize future investments.

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REFERENCES

Armstrong, B.R.: A quantitative analysis of avalanche hazard on U.S. Highway 550, southwestern Colorado. Proc. West. Snow Conf., 49, 95-104.1981

Hamre, D., Greene, E., Margreth, S.: "Quantifying the effectiveness of active mitigation on transportation corridors." Proceedings of the International Snow Science Workshop, Breckenridge CO, 435-441. 2016

Hamre, D, and Hendrikx, J.: Quantified Avalanche Risk Analysis and Peer Review, New Zealand Transport Agency. 2018

Hendrikx, J., Owens, I., Carran, W. and Carran, A.: Avalanche risk evaluation with practical suggestions for risk minimization: A case study of the Milford Road, New Zealand. Proceedings of the International Snow Science Workshop, Telluride, Colorado, USA, 757-767. 2006

Hendrikx, J., & Owens, I.: Modified avalanche risk equations to account for waiting traffic on avalanche prone roads. Cold Regions Science and Technology, 51(2-3), 214-218. 2008

Mears, A: Avalanche Hazard Index for Colorado Highways, Colorado Department of Transportation. 1995

Schaerer, P.A: The Avalanche Hazard Index. Annals of Glaciology, 13, 241-247. 1989