ABSTRACT

This paper explores the notion that the Avalanche Hazard Index can be used for operational analysis of avalanche hazard over time of a specific road using Utah State Route 210 in Little Cottonwood Canyon as an example. It reviews application of the Avalanche Hazard Index (AHI) in various versions. Evaluation is made of proposed additional parameters for the equation including traffic engineering concepts such as fiftieth, thirtieth highest, or peak hour volumes along with other variables identified from 27 years of weather and avalanche occurrence data. The concept of a theoretical maximum AHI value for a given road is introduced. An attempt is made to demonstrate the calculation of an adequate operational safety margin for highway avalanche forecasting. Site specific recommendations are made for the example highway.

KEYWORDS: avalanche hazard, avalanche forecasting, avalanche countermeasures,

1. BACKGROUND

The AHI developed by Peter Schaerer is defined as "a numerical expression of damage and loss as a result of interactions between avalanches and vehicles on the road". It describes the nature and magnitude of resulting damage associated with the frequency of encounter (Schaerer 1989). The index works as an average allowing comparative analysis of disproportionate roads.

It has been utilized in the identification of hazard mitigation priorities, the comparison of avalanche risk and the evaluation of avalanche control methods.

During the winter of 1997 - 98, three unexpected avalanches reached Utah State Route (SR) 210 in Little Cottonwood Canyon involving moving vehicles. Seasoned local avalanche forecasters felt something had changed during their 25 years tenure in the canyon's 54 year modern avalanche history. It was perceived this change had resulted in an increase of the present day hazard from that of years past.

In many operations, hazard is managed through forecasting and control efforts. Forecasting of highway avalanche hazard can be described as a risk based decision made regarding the acceptable level of danger to which the traveler is exposed. This decision is based on the predicted magnitude and nature of avalanches resulting from current and future snowpack instability (after McClung 1997). Control can be described as an attempt to determine the magnitude and time of avalanche occurrence in an effort to reduce losses (life, monetary, and delay) due to encounters.

The actual daily avalanche hazard has very little relationship to the hazard index calculated for the road being managed. Every forecaster is aware of the elements that contribute to either an increasing or decreasing hazard. The methodology has been extensively covered in avalanche science literature. However, it may be possible to utilize the AHI to view data collected over time and evaluate for significant trends of the variables. From this evaluation, it may also be possible to establish mission rules (a term borrowed from the space program) to assist the forecaster in accomplishing the data reduction required to make a forecast for a highway operation.

An assumption is made in this paper that weather conditions and avalanche occurrence remain random events. Discernable patterns are not expected to be associated with these variables in this relationship. Variables for which there is the
potential of control or pattern are the focus of this investigation.

1.1 Review of AHI Application

In its simplest form, the AHI is the sum of the probability of moving vehicle encounter plus the probability of a waiting vehicle encounter for different magnitude and return intervals as expressed by:

\[ AHI = \sum W_j \times (P_{m,ij} + P_{w,ij}) \]  

(1)

where \( P_{m,ij} \) = moving vehicle encounter frequency
\( P_{w,ij} \) = waiting vehicle encounter frequency at path \( i \pm 1 \)

The Avalanche Hazard Index (Schaerer 1974) was first applied to Utah State Route 210 by Duain Bowles generating an index value of 766. He compared this to an index of 126 for US 550 in Colorado and 174 for the Trans Canada Highway at Rogers Pass (Bowles & Sandahl 1987). Later, the Five Mountain Parks Avalanche Study (Statham, Schaerer, Jamieson, & Edworthy 1993) used both Schaerer's detailed AHI along with a simplified form to classify all three of these roads in the Very High Hazard index range.

Art Mears (1995) refined the AHI function to evaluate Colorado Department of Transportation roads. His spreadsheet form of the hazard index calculation was used during 1997 to begin comparison of Utah State Routes affected by avalanches.

Both applications of the AHI to SR-210 involved a simplified version. Comparing each, the product of Mear's spreadsheet incorporating the 1987 values yielded results in line with the expected 0.9 - 0.7 difference (Schaerer 1989) to Bowles earlier numbers.

Important points from Schaerer's work include the completeness with which the function addresses the probability of vehicles stopped by an avalanche being struck by secondary slides. Significant items from Bowles adaptation included solving for uphill / downhill flow and road surface condition, generating a range of values.

2. DISCUSSION OF AHI MODIFICATION

Modification was done so operational related variables could be readily identified and substituted. It made the model more versatile but required more data. Only steps which were altered from the original are discussed. Familiarity with the original work by Schaerer (1989) is assumed. Mear's spreadsheet format was used for its ease of data manipulation. Schaerer's equations provide the base functions for each step. Equation (1) is further expressed as:

\[ P_{m,ij} = \frac{1}{R_{ij}} \cdot \frac{N(L_{ij} + D_s)}{V \cdot 24000} \]  

(2)

where

\( P_{w,ij} \) = moving vehicle encounter frequency
\( R_{ij} \) = return interval of avalanche at path \( i \) of class \( j \) (yrs)
\( N \) = traffic volume (ADT)
\( L_{ij} \) = length of road affected by avalanche at path \( i \) of class \( j \)
\( D_s \) = stopping distance
\( V \) = average speed of vehicle

\[ P_{w,ij} = p_z \frac{N_{w,ij}}{R_{ij}} \]  

(3)

where

\( p_z \) = probability of avalanche on path adjacent (value of 0.15 used, see Armstrong 1981 for a discussion of other values)
\( N_{w,ij} \) = number of vehicles in stopped queue formed by avalanche at paths \( i \pm 1 \) to \( i \pm n \) of class \( j \) (yrs)
\( R \) = return interval of adjacent paths \( i \pm 1 \) to \( i \pm n \) of class \( j \) (yrs)

To address variation in stopping distance, grade, and direction of grade; constant \( D_s \) was replaced in equation 2 with the American Association of State Highway and Transportation Officials (AASHTO) Green Book standard calculation:
\[ D_s = 0.278 V T_r + \frac{V^2}{254 (F \pm G)} \]  

(4)

Where

- \( D_s \) = stopping distance
- \( V \) = average speed of vehicle
- \( T_r \) = reaction perception time (sec)
- \( G \) = the variable for grade in a plus or minus direction (expressed as a decimal)
- \( F \) = the coefficient of friction of tire to roadway surface. 0.18 is used for snowpack from the range of 0.13 - 0.23 (Harrison 1985) 0.59 is used for dry roads (McShane & Roess 1990)

The length of the queue which develops when an avalanche in path \( i \) blocks the road is highly dependant upon the value assigned to the length of road a waiting vehicle occupies. Schauerer and Bowles both used a value of 15 m. Common traffic engineering practices uses an assigned length of a car and a half, approximately 7.6 m (25 ft). In the case of a mixed vehicle type flow, a passenger car equivalent based on the percentage make up of the flow would be necessary. The operational problems associated with this type of change in traffic make up have been addressed elsewhere (Skjonsberg and Morrall 1992). To allow for traffic directional split other than 50/50 and various values for \( L_v \), the following was used:

\[ L_{w,ij} = \sum N_{d-} \frac{N}{24} T_r L_v + N_{d+} \frac{N}{24} T_r L_v \]  

(5)

where

- \( L_{w,ij} \) = length of queue either side of avalanche at path \( i \) for class \( j \)
- \( N_{d-} \) = percent of hourly traffic volume in the direction \( i-1 \)
- \( N_{d+} \) = percent of hourly traffic volume in the direction \( i+1 \)
- \( L_v \) = length of road occupied by waiting vehicle
- \( T_r \) = response time for emergency personnel to arrive

3. TRAFFIC CHARACTERISTICS

3.1 Definitions

Definitions of traffic engineering concepts either previously or potentially included in the AHI are taken from the textbook (McShane & Roess 1990) They include the following:

**Average annual daily traffic (AADT)** is the total number of vehicles passing a given location in a year divided by 365.

**Average daily traffic (ADT)** is an average 24 hour traffic volume at a given location for some period of time less than a year. Daily volumes are useful for planning but cannot be used alone for design or operational analysis.

**Peak hour volume** is the highest measured volume in a specific direction and are used for design and analysis purposes. **Thirty and fiftieth highest hourly volumes** are criteria often used for rural and urban design situations respectively.

**Capacity** is defined by the Transportation Research Board (TRB) Highway Capacity Manual as “the maximum hourly rate at which persons or vehicles can reasonably be expected to traverse a point or uniform segment of a lane or roadway during a given period of time under prevailing traffic, roadway, and control conditions”. Development of delays and queues can indicate flow reaching capacity.

3.2 SR 210 - Little Cottonwood Canyon

Utah SR 210 enters the mouth of Little Cottonwood Canyon at 1634 m (5360 ft) and climbs to 2682 m (8800 ft). Average grade is 9%. The highway provides access to the Snowbird and Alta Ski Resorts along with the Town of Alta. The first avalanche path is at mile marker 5.7. The road ends at mile marker 12.6. There are no options in the lower canyon for traffic to exit off the road forming a true transportation corridor. It is this isolated lower section on which the research in this paper is focused.
Dispersal of traffic begins at milemarker 10, the first Snowbird entry. Multiple parking and limited residential areas absorb the traffic by the end.

In traffic engineering terms, the highway can be described as a mountainous rural two lane dead end road with characteristics of both highly recreational and urban commuter routes. There is a permanent traffic counting station at the mouth of the canyon. Average Annual Daily Traffic (AADT), Peak, 30th, 50th, and 100th highest hour traffic volumes are shown in figure 1.

Volumes are per calendar year and not by winter season. For this study they are felt to be adequate since the extreme majority of the 100 highest hours continue to be on winter operation days. Summer, Spring, and Autumn traffic volumes do not approach those of winter. Future work includes reducing traffic data to seasonal counts.

![SR 210 Traffic Volumes](image)

**figure 1.** AADT, Peak hour, 30th, 50th, and 100th hour values.

Snow and weather observations at the head of the canyon have been recorded since 1944/45. The Utah Department of Transportation (UDOT) Avalanche Safety Program maintains the historical Atwater study plot at 2649 m (8690 ft). Average annual snowfall recorded there from 1 November to 30 April is 1261 cm (496.4 in). Maximum and minimum years are 1905 cm (750 in) and 757 cm (298.1 in) respectively. Average water equivalency is 1143 mm (45 in). UDOT's snow and ice removal policy classifies this road for special treatment to avoid snow accumulation beyond a certain amount.

Of the length, approximately 53% of the centerline distance is either in the track or runout of avalanche paths and subject to deep and plunging avalanches. Above 2135 m (7000 ft) where the greater concentration of paths and snowfall occurs, approximately 71% of the road is affected.

The road from milemarker 10.2 to 11.5 underneath the Superior and Hellgate avalanche paths can be closed and traffic routed around the hazard on the Bypass road maintaining full access to Alta Ski Lifts and the Town of Alta. Nearly all of the day parking in the upper canyon is also threatened by avalanche paths.

4. ANALYSIS OF MISCELLANEOUS VARIABLES

Weather is a primary variable in the development of avalanche hazard. To evaluate the weather's influence we looked at the traffic and posed the question, "Has the traffic volume migrated from a bluebird day to a powder day?" Sufficient data for conclusive reduction was not evaluated and provides opportunity for further study. However, preliminary results showing the percentage of days with peak traffic hour volumes falling either on a no snow or snow day indicate a dramatic trend shown in figure 2.

![Peak Traffic Days, Snow vs No Snow](image)

**figure 2.** Percentage of clear vs snowy days with peak hours.

Another weather-traffic related change is increased mobility of vehicles. This has evolved in two areas. First is the increased percentage of all wheel drive vehicles currently registered than in previous years. The other is increased storm fighting capacity of the winter maintenance fleet including: higher horsepowered and improved...
trucks, plowblades, snowblowers, graders, and dozers; higher efficiency of de-slicking materials. It is now possible to keep the road open during adverse snow conditions. The only reason to delay traffic or close the road is now due to avalanche hazard. The storm generated safety margin of overpowering the snow removal effort is no longer present. This can be seen in decreasing period of closure, 97% of a storm in 1973 to 31% in 1998 for similar storms resulting in avalanches of similar class with return cycles of 5 years.

5. AHI AS APPLIED FOR COMPARATIVE ANALYSIS

Figure 3 shows the AHI calculated for the study segment. A caution should be mentioned here about isolating a segment of road for evaluation. Because the function takes into account hazard on either side of the path evaluated for $P_{cm}$, care must be exercised to include all paths in if they are outside the segment but threaten traffic queues generated by an avalanche inside the segment.

![AHI calculated using AADT](image)

Figure 3. AHI calculated using AADT, upgrade direction, snowpack, at 48kph.

6. AHI AS APPLIED FOR OPERATIONAL ANALYSIS

WADT (winter ADT) is a fixed value. It reflects the averaging of traffic volume over 24 hours and is shown as an averaged hourly volume in figure 4. An hourly graph of an average January 1998 day's traffic flow in both directions is also visible.

![Hourly AHI Values](image)

Figure 4. January 1998 average day's traffic flow both directions with averaged hour from AADT.

The AHI as calculated for the averaged hourly value of WADT is shown in figure 5. Also shown is the AHI calculated for the hour values from in figure 4. It appears from this graph that some one of the hour values may be a better indication of the hazard experienced over the course of an operational day.

![Hourly AHI Values](image)

Figure 5. AHI values calculated from figure 4 data.

To apply the AHI to operation of a given road over a period of time there must be a value introduced for comparison. There is a theoretical maximum hazard ($AHI_{max}$) generated by operation at or beyond capacity. The capacity can be calculated for any road using the Highway Capacity Manual published by TRB. Relation of the calculated capacity to the hourly volumes is shown in figure 6.
A value for $K$ of 20% found in traffic engineering texts compares with the experience of SR 210. Peak hour has evolved from 47.5% in 1970 to 24.8% in 1997. 50th highest hour values have changed from 27.2% to 19.1% over the same period of time. The directional split is 85/15 for Little Cottonwood Canyon. When calculated for the data used in figure 6 and an AHI is formulated, the results appear as shown below.

$$DHV = AADT \times K \times D$$

where $K =$ the proportion of daily traffic occurring during the peak hour expressed as a decimal

$D =$ the proportion of peak hour traffic traveling in the peak hour direction

To further evaluate the hourly AHI, two weightings are applied in figure 9. The weighting factor used is an hourly value $\text{AHI}/\text{AHI}_{\text{MAX}}$ times the peak hours and applied against the higher and lower capacity limits. Apparent in this graph is an $\text{AHI}_{\text{hourly}}/\text{AHI}_{\text{MAX}}$ ratio of 0.90 seems to provide an empirical margin of safety.
figure 9. Close up of AHImax limit area with weightings applied.

6.1 **Discussion of Example Highway**

In the case of SR 210, no encounters occurred prior to any of the 100 highest hours reaching or exceeding calculated capacity. The encroachment of the hourly AHI values into the AHI max limits occurred with only 5% of the 100 highest hours above capacity.

At the present time, road closure time for SR 210 is determined due to logistical constraints. Two hours prior to closure is the decision deadline based on the period required to make notification of all entities affected. Ahead of this time there exist two levels of warning status as found in the Highway Avalanche Control Alert (HACA) guidelines in the appendix.

Returning to the hourly data which generated the graph in figure 4, the uphill traffic count is 3357 vehicles or 3.1 to 5.1 times the hourly capacity. It is clear 2 hours lead time no longer works with uncontrolled traffic volume.

7. **CONCLUSIONS**

a) Comparative analysis using an AHI based on either AADT or WADT needs no additional variables. However to make an operational analysis, hourly traffic volumes are necessary. 50th highest hour appears to be the correct choice in the case of a highly recreational route. Hourly volume for evaluation can also be adequately calculated using equation 6.

b) Extrapolation of maximum hourly AHI based on calculated or observed highway capacity provides greater versatility in use of the function. Additional benefits of capacity investigation were covered in the discussion of the example road.

c) An AHI/AHI_max ratio may be useful in developing and maintaining a safety margin for highway avalanche forecasting and control operations.

d) Access to real time hourly traffic values like weather conditions such as wind is a requirement to highway avalanche hazard forecasting and control operations.

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9. **REFERENCES**


American Association of State Highway and Transportation Officials (AASHTO), 1994. *A policy on the geometric design of highways and streets*.


APPENDIX

UDOT Avalanche Hazard Forecast

NoA  No Action is planned during the next observational period (12 Hrs)

HACA12  Highway Avalanche Control Alert for the next 12 hours. Avalanche Control Actions including but not limited to closure and explosive testing is expected to occur during the next 12 hours.

HACA6  Highway Avalanche Control Alert for the next 6 hours. Avalanche Control Actions including but not limited to closure and explosive testing is expected to occur during the next 6 hours.

CAN2  Control Action Next 2 hours. Closure and control action is being implemented in 2 hours.

Engineering. Prentice-Hall, Inc. 34, 49-52, 63.


Weighting Factor Comparison

Figure 9