BRITISH COLUMBIA MINISTRY OF TRANSPORTATION AND INFRASTRUCTURE PROVINCIAL AVALANCHE HAZARD INDEX

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ABSTRACT: This paper presents work completed to quantify and visualize snow avalanche hazard for the entire provincial highway network as managed by the British Columbia Ministry of Transportation and Infrastructure (the Ministry) in Canada. The project used the Avalanche Hazard Index (Schaerer, 1989) to describe highway avalanche hazard numerically and developed a geospatial tool that can be used for decision-making. The tool allows the identification of avalanche program areas, highway corridors, and specific paths where improved risk mitigation measures would be most beneficial and can support prioritizing avalanche risk mitigation investments. The 62 avalanche hazard forecast areas affecting provincial highways are well known to the Ministry, however changes to avalanche path characteristics, implementation of new avalanche mitigation technologies, changes to traffic volumes, and changing environmental conditions over the past few decades has provided motivation for this new assessment. In order to complete the AHI analysis, Ministry data for relevant highway corridors and avalanche paths were collected from a variety of sources. These included:

- Historical avalanche occurrence records as maintained by the Ministry - 173,869 avalanches.
- British Columbia digital road atlas – data for 196 highway corridor sections (e.g. speed limits, number of lanes).
- Ministry Traffic Data Program database – traffic volumes.
- Ministry digital avalanche path mapping – widths and locations for 1546 paths.
- Ministry avalanche path atlases – general data for the paths.
- Historical aerial photographs – analysis of hundreds of aerial photographs dating back to 1937 was used to refine avalanche path dimensions.

These data were then adjusted based on interviews with key Ministry personnel combined with expert judgment. The resulting dataset was stored in a geodatabase and analyzed with an automated algorithm to calculate AHI values following the commonly accepted methodology outlined in Schaerer (1989). Data-driven methods were employed for the AHI input parameters wherever reasonable. The calculated AHI values are hosted on a web-based Geographical Information System (GIS) dashboard that promotes user-friendly interaction and scenario testing with the data. The interactive dashboards allow testing of various mitigation scenarios (e.g. how does the addition of an avalanche deflection berm to an identified path affect the AHI value for an avalanche area or highway corridor?). Relative differences in AHI values and subsequent amount and type of mitigation can be compared between different highway corridors.

KEYWORDS: British Columbia, Ministry of Transportation and Infrastructure, Avalanche Hazard Index, Transportation corridor risk, Risk planning tool, AHI

1. INTRODUCTION

The British Columbia (BC) Ministry of Transportation and Infrastructure (the Ministry) operates one of the largest highway avalanche risk management programs in the world. After a notable tragedy in the early 1970s, the BC government implemented an Avalanche Task Force to better understand the hazard and develop mitigation strategies to manage risk to the travelling public. The work included developing an Avalanche Hazard Index (AHI) to better quantify the risk to highway users (Avalanche Task Force, 1974; Schaerer, 1989). Avalanche control programs were implemented in various

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regions throughout BC and have been in operation for several decades.

The avalanche control programs have largely been successful and have adapted to various changes over the years (e.g. highway upgrades, evolving traffic patterns). Since 1991, there has not been a comprehensive province-wide study to assess the avalanche hazard and evaluate the avalanche mitigation strategies in place. In addition, most historical avalanche path maps had not been updated to reflect evolving roadway alignments and updated avalanche characteristics (i.e. extent, magnitude, and frequency).

Based on findings and recommendations from an internal audit completed in 2021 the Ministry commissioned a project to update mapping and calculate the AHI for the entire provincial highway network. In addition, the Ministry requested that the AHI results be presented within an interactive GIS-based platform that allows for both data visualization and scenario testing. All work was to be completed as a desktop project, with no field surveys.

This paper summarizes the work completed to calculate AHI for the Ministry highway corridors and develop the GIS platform and interactive dashboards.

2. AVALANCHE HAZARD INDEX BACKGROUND

AHI is defined as "a numerical expression of damage and loss as the result of the interaction between snow avalanches and vehicles on a road." (Schaerer, 1989). Although it is technically not considered a Quantitative Risk Analysis, it is intended to provide a measurement of risk to the traveling public along a highway segment that can be evaluated and compared to other highway segments. It has utility in the ability to determine which avalanche paths contribute most to the hazard, and to analyze the effect of various mitigation strategies, which can be useful for communicating business cases for infrastructure funding.

Numerous AHI studies have been completed for highways in several locations in North America (e.g. Parks Canada, 1993; Colorado Department of Transportation, 1995; Hamre et al., 2023), as well as New Zealand (e.g. Owens and Fitzharris, 1985; Hendrikx, 2005). In addition, AHI studies have also been completed for railway corridors (Hamre, 2009), hiking trails, and snowmobile trails.

3. DATASETS

The datasets used for the project were developed from highway traffic and avalanche path databases maintained by the Ministry. Specifically, the BC digital road atlas (GeoBC, 2022) provided detailed information about all highway road corridors in BC, including core resource roads. 196 total distinct corridors were created. The Ministry traffic database provided traffic volumes from both short and permanent core counters. Ministry digital avalanche path polygons, avalanche occurrence records (173,869 recorded avalanches), and avalanche atlases dating back to the late 1970s provided the primary data describing over 1,546 avalanche paths. One hundred and seventy-seven historic aerial photos were analyzed dating back to 1937.

4. METHODS

A detailed description of specific data-driven methods can be found in a concurrent ISSW paper (Thumlert et al., *in prep*). Overall, residual AHI (AHI_R) values were calculated for the entire Provincial highway as managed by the Ministry. The AHI_R describes the risk situation after considering all current mitigation measures (e.g. hazard forecasting and road closures, explosives control, catchment ditches), whereas the unmitigated AHI reflects the risk situation assuming no mitigation measures.

Given the project scope and budget constraints (e.g. no field work, large datasets, objective to test mitigation scenarios), we developed an automated algorithm in the R programming language (R Core Team, 2022) to run the entire provincial AHI calculations. The algorithm enables rapid recalculation of AHI values as the quality of the input data improves (e.g. with more avalanche observations), and for the interactive dashboard scenario testing. The algorithm also allows the capability to analyze large amounts of data quickly, however data input and outputs still must be checked for quality. Ministry Avalanche Technicians from each program area were interviewed to refine return period estimations, traffic characteristic data, and to describe the existing avalanche mitigations. These interviews were deemed critical for this project and are recommended whenever data-driven automated calculations are used.

5. RESULTS

AHI_R values representing avalanche risk for the Ministry avalanche hazard forecast areas are shown in Table 1. These AHI_R represent the risk situation after considering all existing mitigation measures (e.g. hazard forecasting and road closures, explosives control, catchment ditches). Once calculated, AHI_R values were classified into index levels according to Table 2 for interpretation by the

Ministry. In relative terms, the higher the AHI_R, the more hazardous the area is. AHI values are correlated with winter average daily traffic volumes which are also shown in Table 1.

Table 1: Summed residual AHI (AHI_R) values for each Ministry avalanche hazard forecast area with the corresponding estimated winter average daily traffic and AHI_R classification (Table 2). Note that avalanche areas with "Very Low" AHI_R classification are not listed as these were deemed insignificant.

Avalanche Area	AHI_R Total	WADT	AHI_R Class
TCH West of Revelstoke	150.6	5877	VERY HIGH
Bear Pass	109.4	210	HIGH
Kootenay Pass	108.9	1109	HIGH
Exstew to Rainbow Summit	85.9	945	HIGH
Fraser Canyon	48.6	1676	HIGH
TCH East of Revelstoke	45.9	4823	HIGH
Blueberry Paulson	41.9	2496	HIGH
Bridge River	31.4	250	MODERATE
Lardeau	31.0	597	MODERATE
Red Pass	24.6	2260	MODERATE
New Denver - Kaslo	21.7	685	MODERATE
Duffey Lake	20.5	1124	MODERATE
Golden East	20.4	4973	MODERATE
Grand Forks North	18.5	590	MODERATE
HWY 23 North	18.0	719	MODERATE
Coquihalla	13.7	8444	MODERATE
Cape Horn Bluffs	11.5	626	MODERATE
Whitewater	11.2	1800	MODERATE
Coffee Creek	9.3	1354	LOW
Alison Pass	7.1	2090	LOW
Toby Creek	5.5	500	LOW
Bella Coola	5.3	160	LOW
Telegraph Creek	5.2	45	LOW
Sea to Sky	4.3	7690	LOW
Big Slide	4.1	975	LOW
Fernie	3.4	4218	LOW
Highline	2.4	75	LOW
Castlegar Bluffs	2.1	1425	LOW
Highway 5a	1.9	803	LOW
Chase	1.8	6265	LOW
Galena Pass	1.7	50	LOW
Mt.Cheams Floods	1.6	10937	LOW
Barrière	1.5	2278	LOW
Marble Canyon	1.1	581	LOW

Table 2: Avalanche Hazard Index Levels (Stethem et al., 1993).

Rating	Avalanche Hazard Index
Very Low	<1
Low	1 - 10
Moderate	10 - 40
High	40 - 150
Very High	>150

6. INTERACTIVE DASHBOARDS

GIS dashboards are interactive map-based platforms designed to display, analyze, and visualize spatial data in a user-friendly manner. They combine the ability of GIS to capture, store, manipulate, analyze, manage, and present spatial data with the interactivity and visual clarity of a responsive information dashboard.

A collaborative design approach for the Ministry project led to two modules built on the ArcGIS Online platform and supported by FME (Feature Manipulation Engine) Cloud's data transformation engine: 1) an Authoritative module, and 2) a Sandbox module. Both modules featured dashboards offering location-based analytics and visualizations across multiple spatial scales – province wide, program areas, forecast areas, highway corridors, a single path or group of paths (Figures 1 and 2).

The Authoritative module functions as the primary repository for validated, official data records providing a reliable reference for stakeholders. In contrast, the Sandbox module serves as a dynamic workspace for hypothesis testing and scenario modeling. It provides users with the freedom to modify input parameters and evaluate potential outcomes without altering official records. Although feature geometries are locked, attributes such as return period, length of road affected, traffic volume, and response times can be edited via a web mapping interface and then associated AHI values can be recalculated immediately. This functionality enables the decision makers to evaluate the effect of potential mitigation options (e.g. diversion berm, avalanche shed, re-alignment of the highway, catchment ditches) or the potential effects of changing traffic patterns (e.g. highway closure with traffic rerouted through different corridor, added traffic lane). Resulting scenarios can either be exported or reset to reflect the authoritative dataset.

Together, these GIS dashboards offer a holistic solution for data management, interaction, and planning. They provide a valuable tool for decision-makers and are easily scalable to a variety of scenarios.

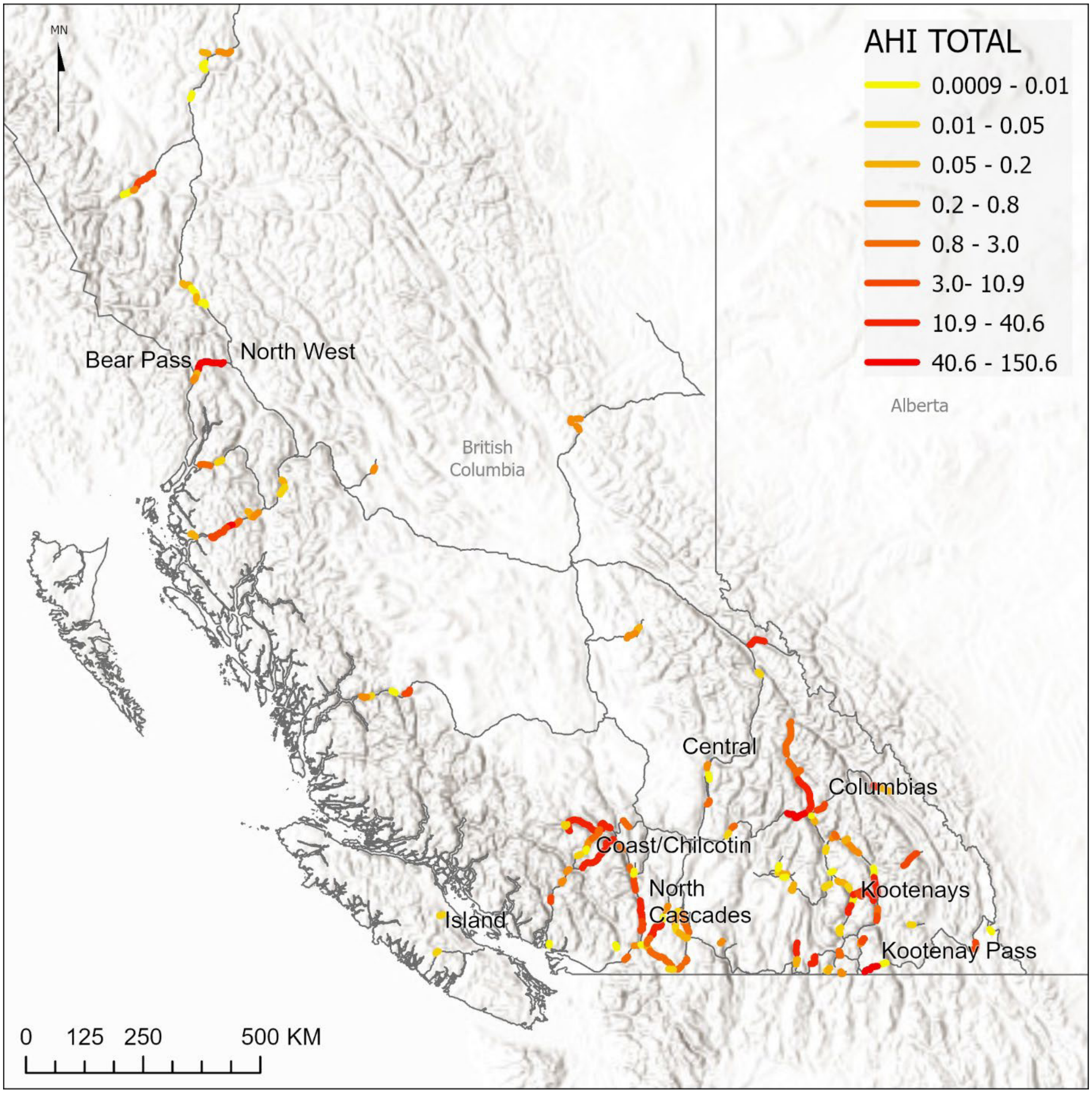

Figure 1: Map showing AHI totals for highway corridors managed by the Ministry across British Columbia. Labels show approximate locations of the main Ministry avalanche programs.

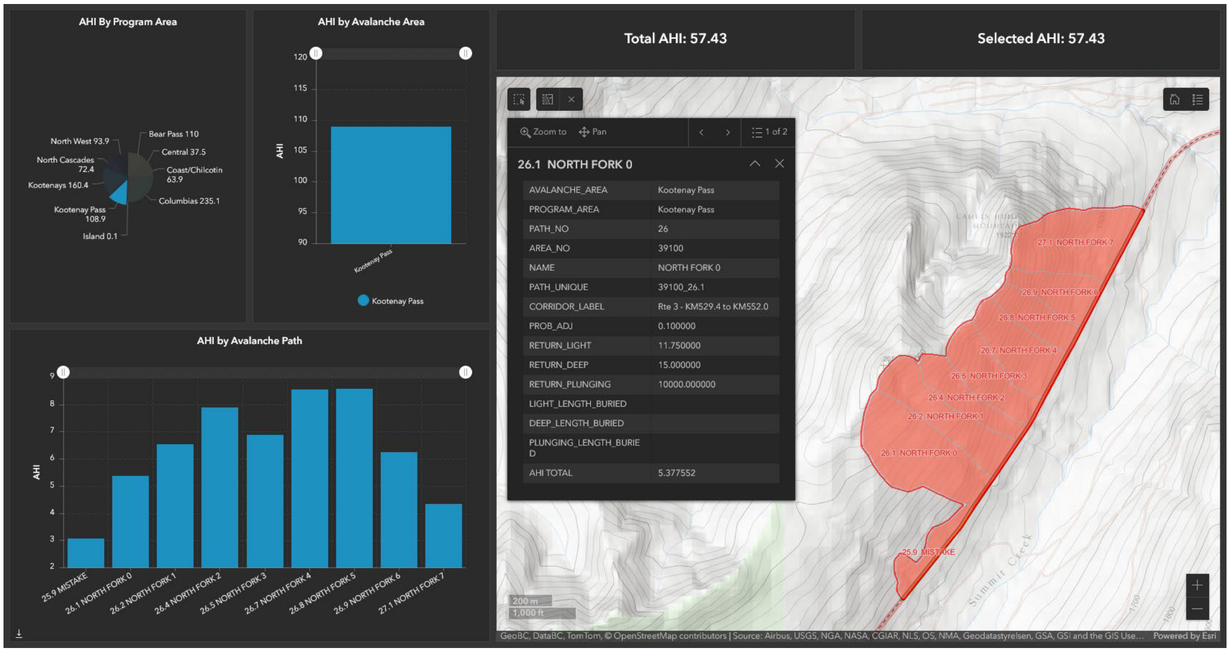

Figure 2: The sandbox dashboard displaying AHI values and avalanche path parameters for the "North Fork 0" path located along Highway 3 in Kootenay Pass located in the Ministry's Kootenay Pass program. The "Total AHI" field shows the summed AHI values for all paths in the map viewer. The "Selected AHI" field shows the AHI value for the single selected "North Fork 0" path. The AHI by Program Area and Avalanche Area graphs show AHI values for these Ministry-specific groupings and they can be clicked on to zoom the map scale to these areas.

7. DISCUSSION

7.1 *Interpreting Avalanche Hazard Indices*

The relative differences in AHI values between different highway corridors allow the comparison of the amount and type of risk mitigation. For example, how do avalanche mitigation measures for highways with similar AHI values in different jurisdictions compare? The AHI indices presented in this paper show values for the individual avalanche paths, however it is important to understand that the total AHI value for a specific path includes the contribution from avalanches in adjacent paths impacting traffic backed-up due to a blocked highway. That is, mitigation measures may be best applied to the adjacent path if that scenario contributes the most to the AHI score.

AHI values are often used to identify avalanche paths and corridors where increased control or mitigation would be most effective. However, other factors contribute to prioritizing avalanche risk mitigation investments. Notably, potential risk mitigation investments often do not eliminate avalanche hazard for entire highway corridors, therefore existing avalanche forecasting and control programs will typically continue to be relied on. Integration of potential mitigation measures with existing programs must be considered. Increasing efficiency and safety for existing control programs are important factors not readily assessed by solely considering AHI values. A good example of this is the TransCanada Highway #1 west of Revelstoke where recent mitigation investments (installed remote avalanche control systems) has dramatically improved efficiency and safety for the avalanche control program, even though the AHI_R remains elevated.

7.2 *Further Analysis*

Unmitigated (natural state) AHI values are often compared with AHI_R values to evaluate the effectiveness of existing avalanche risk mitigation measures. However, natural avalanche magnitude and frequency – assuming no mitigation measures – are often challenging to estimate and require expert judgement.

Forecasting future AHI values for highway corridors based on expected increases in traffic volume can provide insights to where future avalanche hazard for highway users is likely to exist. Standard regression analysis on historical traffic volume data is typically used and provides estimates for percentage increase in traffic by corridor. The AHI values presented here assume uniform daily traffic volumes, where in reality, traffic volumes often intensify at distinct times of the day (e.g. ski resort traffic peaks to the resort in the morning and away from the resort in the afternoon). Calculating separate AHI estimations for these higher traffic intensity times may provide more realistic understanding of avalanche hazard.

A comparative analysis of Ministry AHI studies (e.g. the 1974 Avalanche Task Force, the 1991 15-Year Review, 2022 Coquihalla Mitigation Analysis) over time could be undertaken. The increase or decrease of AHI values for Ministry Avalanche areas and Program areas could be analyzed and explained by major changes to traffic patterns, improved mitigation measures, or other significant changes. This analysis would provide insights into the key drivers of avalanche hazard for highway users and further aid in planning decisions.

Substantial quality control of the AHI source data was completed during the analysis, however there was a limit to the extent of data checking that could be completed within the project budget and scope. Field studies that investigate return period estimates, length of road affected, and probabilities of subsequent releases would be expected to increase the robustness of the results. In addition, specific traffic studies that focus on actual traffic volumes through avalanche areas, as well as the nature of traffic flow would aid in understanding the relevance of AHI for a specific avalanche area (e.g. a ski area access road where 'rush hours' occur).

7.3 *Future development*

Given the rapidly advancing landscape of GIS technology and the increasing emphasis on data-driven decisions, future developments for Dashboards could include:

- Flexible Feature Geometry: A significant enhancement to the scenario modeling functionality would be to support the backend processing of geometry, allowing users to modify the interaction of path and road features. This would permit more intricate scenario testing and offer insights into spatial adjustments and their implications.
- Batch Editing: By batching changes to multiple features, it becomes easier to correlate different parameters. Large-scale, simultaneous modifications to features could be especially useful to model and visualize areas at increased risk due to changing climatic factors.
- Real-time Data Feeds: Integrations with Internet of Things (IoT) sensors such as the Road Weather Information System (RWIS) placed in risk-prone areas could provide real-time updates on conditions, allowing for a time series analysis of AHI.
- Public Access: A controlled public access layer could allow stakeholders to access basic risk assessments, fostering transparency and community engagement.

8. SUMMARY

This paper presents work done to quantify and visualize snow avalanche hazard for the entire BC provincial highway network as managed by the Ministry. The AHI – a numerical expression of avalanche hazard – was used to create a valuable geospatial tool for decision-making. The tool allows the identification of avalanche program areas, highway corridors, and specific paths where improved risk mitigation measures would be most beneficial and can support prioritizing avalanche risk mitigation investments.

Input data were mined, analyzed, and then adjusted based on interviews with key Ministry personnel and combined with expert judgment. The resulting dataset was stored in a geodatabase and analyzed with an automated algorithm to calculate AHI values. Data-driven methods were employed for the AHI input parameters wherever reasonable. The calculated AHI values are hosted on a web-based GIS dashboard that promotes user-friendly interaction and scenario testing with the data. The interactive dashboards allow testing of various mitigation scenarios (e.g. how does the addition of an avalanche deflection berm to an identified path affect the AHI value for an avalanche area or highway corridor?). Relative differences in AHI values and subsequent amount and type of mitigation can be compared between different highway corridors.

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