PRIORITIZING AVALANCHE MITIGATION MEASURES FOR THE TRANS-CANADA HIGHWAY THROUGH GLACIER NATIONAL PARK

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ABSTRACT: The Trans-Canada Highway (TCH) through Rogers Pass in Glacier National Park (GNP) is a critical transportation corridor within British Columbia, and a vital link in Canada's national highway network. The TCH is threatened by 134 avalanche paths through GNP, which cause an average 74 hours of closure per winter and pose significant risk to highway users and workers. Winter average daily traffic through GNP continues to increase every year and, without further avalanche mitigation, will lead to increased risk to highway users and likely increase the frequency and duration of closures.

In 2015, the Parks Canada Agency initiated the TCH - Avalanche Mitigation Project for GNP, which aims to reduce avalanche risk to highway users and workers, reduce closure time, and optimize the efficiency of current avalanche risk management operations. Mitigation measures were evaluated using six scoring metrics based on the project objectives. Selected mitigation measures included: permanent avalanche defences, remote avalanche control systems, and a comprehensive avalanche detection network. The mitigation measures selected for construction, and their respective improvement in highway safety and reliability, are summarized. Construction of mitigation measures began in 2016 and will be completed in 2020. This project constitutes the largest permanent infrastructure improvements to the avalanche program since construction of the highway was completed in 1962.

KEYWORDS: Avalanche protection, avalanche risk, highway, risk analysis, project management.

1. INTRODUCTION

The Trans-Canada Highway (TCH) and Canadian Pacific Railway (CPR) between Revelstoke and Golden, BC pass through Glacier National Park (GNP), at the center of which is Rogers Pass (1330 m). The safety and reliability of this corridor has a direct and significant effect on the economy of the province and the country (NovaTrans, 2010), and relies heavily on effective avalanche control in the winter months.

The TCH and CPR through GNP are affected by 134 avalanche paths, making it one of the most challenging avalanche programs for a transportation corridor in the world. Planning and control of the associated risks is the responsibility of the Parks Canada Avalanche Control Section (ACS) with support from the Department of National Defence (DND).

In 2015, the Parks Canada Agency initiated the TCH - Avalanche Mitigation Project, with the objectives to reduce avalanche risk to highway users and workers, reduce closure time (improve reliability), and optimize the efficiency of current avalanche risk management operations. Additional work includes the rehabilitation of existing snow sheds, increased traffic storage areas (for avalanche closures), and sections of highway improvements (addition of passing lanes). This project constitutes the largest infrastructure improvements to the avalanche program since construction of the highway was completed in 1962. While the scope includes major infrastructure development, budgetary restrictions precluded the construction or extension of snow sheds.

Mitigation measures were evaluated using six scoring metrics based on the project objectives. The selected mitigation measures included: permanent avalanche defences, remote avalanche control systems (RACS), and a comprehensive avalanche detection network.

2. BACKGROUND

2.1 Current avalanche mitigation measures

Avalanche control in GNP relies on an extensive artillery control program, using two 105 mm Howitzers fired from 17 roadside gun platforms. To control the 134 avalanche paths, an average of 700 rounds per year are fired at 270 unique targets.

The targets are pre-registered, so artillery can be fired day or night in any weather. The guns average 1 round every 4 minutes, including targeting, firing, and observation of avalanches. Avalanche control is conducted using two main closure blocks on each side of the Rogers Pass summit. Two additional closure blocks on the east and west boundaries of GNP

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are used less frequently. Avalanche control by helicopter is used as a supplementary method, primarily in the spring after the DND is demobilized.

In addition to the avalanche control program, permanent defence structures are used in some avalanche paths, including five snow sheds, braking mounds, diversion and retaining berms, benches, catchment basins, fences, and snow nets. Most defences were built prior to 1962 during construction of the TCH (Schaerer, 1962). Most recently the fifth snow shed was added in 1979.

2.2 Highway Reliability

From 1979 to the present day, the winter average daily traffic (WADT) increased from approximately 1000 vehicles per day (vpd) to over 3000 vpd. Despite significant improvements in the avalanche risk management operations, increasing traffic without changes in defence structures has increased the Avalanche Hazard Index (AHI) (Schaerer, 1989).

From 1979 to 2014, GNP averaged 42 closures per winter, with an average of 74 closure hours per winter. While 74% of the closures are 2 hours or less (for avalanche control), most winters had at least one closure greater than 12 hours in duration (preventative and/or deposit removal). Despite an increase in WADT, average annual closure time has remained relatively constant since 1979.

2.3 Baseline avalanche risk in GNP

Of the 134 avalanche paths that affect the TCH through GNP, 70 paths have return periods to the TCH of 10-years or less. From 2000 to 2015, a total of 55 avalanches greater than Size D2 have affected the open highway, an average of just less than 4 per year. Avalanche paths that routinely reach the open highway present a significant risk to highway traffic and thus rank highly in terms of mitigation priority.

Calculation of the AHI for the TCH through GNP provides a baseline index under the current avalanche program (i.e. artillery control and existing permanent defences) and uses the frequency of natural and controlled avalanches affecting both the open and closed highway. The Residual AHI (RHI) is also calculated and reflects the residual risk under the current program; RHI only considers the frequency of uncontrolled avalanches affecting the open highway.

The AHI for Rogers Pass increased from 235 in 1987 (Schaerer, 1989) to 249 in 2010 (Novratrans, 2010) and in 2016 was estimated to be 301, or Very High, and is one of the highest in North America. This trend is largely attributed to the increase in WADT.

By 2020, WADT through GNP is predicted to increase to over 4000 vpd. Without further avalanche mitigation, the AHI is expected to increase due to higher traffic volumes (Table 1), which represents an increase in risk to highway users and will likely increase the frequency and duration of closures due to limited traffic storage capacity at the closure points.

Table 1. AHI and RHI estimates for GNP in 1987, 2010 and 2016; 2020 and 2030 estimates (shaded grey) assume no changes to permanent defences.

Year	*1987*	*2010*	*2016*	*2020*	*2030*
WADT (Vehicles/day)	1700	3000	3395	4856	5635
AHI	235	249	301	350	455
RHI	27	~	21	25	30

3. METHODS

A systematic method to assess risk and the benefits of mitigation measures is key for successful management of avalanche hazards (Rheinberger, 2009). To develop an overall avalanche mitigation strategy for GNP, mitigation options at each avalanche path affecting the TCH were evaluated using six scoring metrics, including: (1) reduction of Avalanche Hazard Index and (2) reduction of Residual Hazard Index, (3) effect on highway closure time, (4) effect on efficiency of the current avalanche control program, (5) effect on future highway four-laning, and (6) capital cost.

Ideally, costs and benefits of mitigation measures are monetized to provide a common reference frame (Rheinberger, 2009); however, the monetization of all metrics was not practical. For example, the cost of closures on the TCH is not well understood without an extensive economic analysis. The metrics also have overlapping effects, so attribution of discrete costs and benefits to each is complex. Thus, this method uses both quantitative (e.g. AHI) and qualitative metrics (Jamieson, 2018). To establish a common reference frame, values for each metric were normalized to the range of 0 to 1, thus the sum of the six normalized metrics for a given mitigation measure has a maximum of six points.

3.1 Avalanche Hazard Index and Residual Avalanche Hazard Index

The AHI and RHI were calculated for every path in GNP using avalanche occurrence data from 1964-2015 (baseline). The change in return period to the TCH at each avalanche path was estimated based on the anticipated effect of the proposed mitigation. The AHI and RHI were recalculated using the revised return periods. The difference from baseline values reflects the estimated risk reduction due to the proposed mitigation.

3.2 Closure Time (Reliability)

A weighted average of closure time per avalanche path was estimated by dividing the average annual TCH closure time by the average annual number of rounds fired in each avalanche path. This proved an effective method to rank the contribution of each avalanche path to the total closure time; however, time saved by each mitigation option is difficult to evaluate for 134 avalanche paths. Therefore, each proposed mitigation option was given a semi-quantitative ranking from 1 to 5 to represent its effect on overall closure time (Table 2).

Table 2. Ranking method for reduction in closure time.

Value	*Reduction of Overall Closures Time*
1	No change or negligible effect.
2	Minor change (Reduction < 60 minutes, on average every 5-10 years).
3	Moderate change (Reduction < 60 minutes, on average every 2 – 4 years).
4	Significant change (Reduction by < 60 minutes, annually).
5	Major change (Reduction > 60 minutes, annually).

3.3 Efficiency of the Current Avalanche Control Program

The current avalanche control program operates with high efficiency, controlling the two main closure blocks in approximately 2-3 hours each. Typically, two breaks in the closure are required to clear traffic due to limited traffic storage capacity near the closure points. Closures for avalanche control require coordination with the adjacent provincial jurisdiction and the CPR. The storage of traffic, coordination of highway and rail closures, and implementation of artillery control result in a logistically complex program.

New mitigation measures should not increase complexity nor decrease the efficiency with which closures and avalanche control are conducted. New mitigation measures which require more resources or disrupt the control sequence were considered to have a negative impact on operational efficiency. Each proposed mitigation option was given a ranking from 1 to 5 based on the qualitative change in the program efficiency. A score of 1 represents a decrease in efficiency (e.g. placing RACS within the core artillery program, requiring a control method change), while a score of 5 represents a major increase in efficiency (e.g. placing RACS at peripheral areas eliminating the need for artillery control).

3.4 Future Highway Four-Laning

Future highway expansion to four lanes required consideration for selection of mitigation measures. No designs were available during this work, so a corridor width of 100 m centered on the current TCH was assumed. A four-class ranking was given to each mitigation measure considered; a score of 1 represents a full loss of the benefit of the measure (e.g. concrete stopping wall adjacent to the highway requiring removal during highway expansion), while a score of 4 represents a measure unaffected by highway expansion (e.g. RACS placed in a starting zone).

3.5 Capital Cost

The capital cost of each mitigation option was estimated based on recent construction costs of similar projects. Given the large number of options being considered, cost estimates were approximated by order of magnitude.

4. RESULTS

Each of the 134 avalanches paths was ranked based on the sum of their normalized scores from the six scoring metrics. High ranking paths were grouped based on geographic location (i.e. adjacent paths with a shared mitigation strategy). Avalanche paths selected for mitigation were classified into phases for construction based on rank, ease of design and construction and economic consideration. Results are summarized in Table 3 and described below.

Phase 1 was implemented under a fast timeline prior to the detailed analysis of mitigation options due to fiscal planning requirements. Thus, the selected mitigation relied strongly on the experience of ACS avalanche forecasters.

Phase 1A, completed in 2016, involved the installation of RACS (8 units) in three avalanche paths (Fidelity, Park One and Fortitude). This eliminated the use of artillery at the western boundary of GNP, allowing this area to be controlled concurrent with artillery in other areas, and closures to be more easily coordinated with the adjacent provincial jurisdiction.

Phase 1B, completed in 2017, involved the installation of 1886 lineal metres of snow nets in three avalanche paths (Cougar Corner 6, 7 and 8) and 55 m of debris flow barriers to accommodate a deep gully (Cougar Corner 7). These avalanche paths have a history of avalanches affecting the open highway. Thus, permanent mitigation of these paths results in a large decrease in AHI and RHI.

Phase 2A targeted the prevention of avalanche debris over-spilling and burying the east portal of the Tupper 1 snow shed. An extension of the existing earth diversion berm and a cantilevered wing wall were evaluated; however, structural loading issues on the 55-year-old snow shed prevented construction at this time.

Phase 2B, completed in 2017, involved the installation of RACS (5 units) in two avalanche paths (Cutbank East and Minor) near the eastern boundary of GNP. These paths only affect the CPR but required the closure of the TCH to perform avalanche control with artillery from the highway. RACS eliminated the need for artillery and the paths are now controlled without closing the TCH, resulting in a reduction in closure time and a gain in operational efficiency.

Phase 3A evaluated diversion and retaining berms in the Abbott 3 and 4 avalanche paths. Budgetary constraints, geotechnical challenges and cultural landmarks precluded selection of these measures.

Phase 3B, scheduled for completion in 2019, involves a large retaining berm in the Mounds path to reduce the return period of a large glide slab to the TCH to 30-years. The glide slab releases from the track of the avalanche path each year and has a return period to the TCH of 8-years. The release is not predictable inside of a period of several days and it is not possible to release artificially. The glide slab has a typical release depth of 5-8 m and a size of D4 when it reaches the TCH, which is historically open at the time of release. The deposit requires many hours to remove before the highway can be reopened.

Mitigation of rock cuts forming short slope avalanche paths on the eastern side of GNP were considered for Phase 3C. These locations present avalanche and rock fall hazard and reduction of both was sought (Gauthier, 2016) through enlargement of catchment ditches and installation of barrier walls. Rockfall mitigation design was identified as the critical design pathway and such mitigation is expected to partially or fully mitigation avalanche risk at these locations.

Phase 3D will entail the installation of an avalanche detection network composed of 13 infrasound arrays and four Doppler radar units which augment the network at critical avalanche paths presenting forecasting challenges or where confirmation of avalanche control results is important to ensure risk reduction. Benefits include improved timing of closures and control through early warning of avalanche activity, increased confidence in control results (e.g. during periods of poor visibility or at night) and increased worker safety due to reduced pressure to directly observe controlled avalanches.

Phase 4 is currently in the final design phase and consists of further earthworks projects. Permanent defences for highways in Canada are typically designed for 30- to 100-year events (CAA, 2016). However, the construction of diversion or retaining berms large enough to meet this level of risk reduction was not always possible due to terrain and cost limitations, thus the principal of reducing risk to a level *as low as reasonably practicable* (ALARP) is applied (CAA, 2016; Jamieson, 2018).

Phase 4A includes the enhancement of a catchment basin and the addition of a retaining berm at the Tupper Minor avalanche path. This path affects the TCH annually, including 5 events on the open highway in the past 15 years. The enhanced catchment and berm will decrease the return period to greater than 10-years.

Phase 4B entails the enhancement of the ditch in the Cougar Corner 7 and 8 paths to improve catchment for small (e.g. Size D2) avalanches, which have been observed to initiate below the snow nets in the steep track of these paths. This further reduces the return period to the TCH at this important location.

Phase 4C evaluated design concepts for the enhancement or new construction of large retaining berms in six avalanche paths. With consideration of total cost and ease of construction, the only mitigation measure selected for construction is a large retaining berm in the Cougar Corner 2 path. The return period will be decreased from annual to greater than 10-years.

Table 3. Summary of results by avalanche path and recommended mitigation measures.

Phase	*Avalanche Path Name (Rank)*	*Mitigation Description*	*Selected for Construction*
1A	Fidelity (12); Park One (10); Fortitude (20)	RACS - 8 units	Yes; Complete 2016
1B	Cougar Corner 6 (3); Cougar Corner 7 (1); Cougar Corner 8 (8)	Snow/debris nets (1941 m)	Yes; Complete 2017
2A	Tupper 1 (4)	Extension of diversion berm or construction of wing wall	No; Structural loading issues on the existing snow shed
2B	Cutbank East (7); Cutbank Minor (11)	RACS - 5 units	Yes; Complete 2017
3A	Abbott 3 (2); Abbott 4 (14)	Retaining berms	No; Geotechnical concerns, high cost
3B	Mounds (5)	Retaining berm	Yes; Planned completion 2019
3C	Heather Hill (13); Fences East (22); Beaver Screen (26); Beaver Hill (28); East Gate (38)	Catchment ditches and installation of barriers	No; Rock fall mitigation will partially or fully mitigate avalanche hazard
3D	Ross Peak (9); Abbott 3 (2); Abbott 4 (14); MacDonald West Shoulder 1-4 (16)	Avalanche Detection Network	Yes; Planned completion 2019
4A	Tupper Minor (6)	Catchment basin and construction of retaining berm	Yes; Planned completion 2020
4B	Cougar Corner 7 (1); Cougar Corner 8 (8)	Enhancement of catchment ditch	Yes; Planned completion 2020
4C (1)	Cougar Corner 2 (15)	Retaining berm	Yes; Planned completion 2020
4C (2)	Camp West (24); Mannix (21); Cougar Corner 3 (27) & 4 (19); Gunners 1 (30) & 2 (25)	Retaining berm	No; High cost for moderate ranking paths

4.1 Reduction in AHI and RHI

The reduction in AHI upon project completion is anticipated to be 27%, from 301 in 2016 to 220 in 2020. The reduction in RHI upon completion of the project is 14%, from 21 in 2016 to 18 in 2020 (Table 4). These changes in the AHI and RHI also reflect the projected increase in WADT as shown in Table 1. The increase in AHI resulting from an increase in traffic volume is quite substantial. Had no mitigation measures been added, AHI would increase based on projected WADT from 301 (calculated, 2016) to 350 (projected, 2020), an increase of 14%. Reductions in AHI and RHI are summarized in Table 4.

Table 4. Cumulative reduction in AHI and RHI by mitigation phase.

Phase	*WADT*	*AHI*	*RHI*	*AHI % Change*	*RHI % Change*
1A	3501	304	20.7	0.0%	0.0%
1B	3765	285	21.2	-6.3%	2.5%
2B	3765	285	21.2	0.0%	0.0%
3B	3921	266	20.3	-6.7%	-4.3%
3D	4076	266	20.3	0.0%	0.0%
4A	4076	236	18.0	-11.4%	-11.4%
4B	4076	234	17.8	-0.7%	-1.1%
4C	4076	220	17.5	-5.8%	-1.6%

4.2 Improvement in Highway Reliability

Closure time, or a reduction thereof, is difficult to attribute to a single mitigation measure. Estimates were made based on reduction in artillery control (number of targets in a path regularly fired multiplied by average firing time per round) and deposit removal (using historical frequency and closure data from avalanches affecting the highway). A reduction in closure time of 17% is estimated by project completion in 2020. Given an annual average of 74 hours of closure, this represents an average annual reduction of approximately 13 hours of closure. Estimated reduction in closure time is summarized by phase in Figure 1.

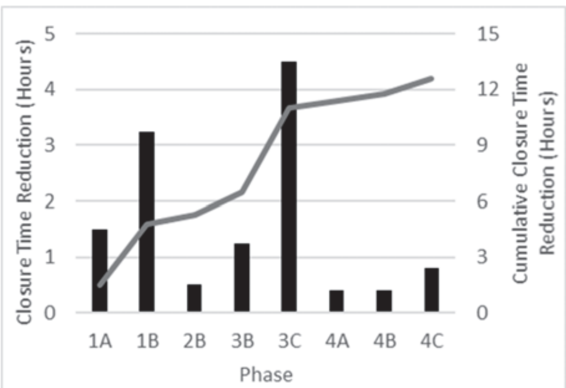

Figure 1. Estimated reduction in closure time by phase.

5. SUMMARY

Objectives of the TCH - Avalanche Mitigation Project in GNP include reducing avalanche risk to highway users and workers, reducing closures, and optimizing the efficiency of the current operations program. A systematic method to assess risk and the benefits of mitigation measures was applied using six scoring metrics, including: (1) reduction of Avalanche Hazard Index and (2) reduction of Residual Hazard Index, (3) effect on highway closure time, (4) effect on efficiency of the current avalanche control program, (5) effect on future highway four-laning, and (6) capital cost. To establish a common reference frame, scores for each metric were normalized to the range of 0 to 1, and the sum of the six normalized metrics for a given mitigation measure has a maximum of six points.

A total of eight mitigation measures were selected for construction in 18 avalanche paths. Selected mitigation measures included: permanent avalanche defences, remote avalanche control systems, and a comprehensive avalanche detection network. Construction of these mitigation measures began in 2016 and will be completed in 2020. Upon project completion the AHI and RHI are anticipated to be reduced 27% and 14%, respectively. A reduction in closure time (improvement in reliability) is estimated at an annual average of 17%, or 13 hours.

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