A MULTI-FACTOR APPROACH TO RANK AND MANAGE THE IMPACT OF AVALANCHES ON HIGHWAY OPERATIONS

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ABSTRACT: Either explicitly or implicitly, avalanche safety operations sort potential avalanche events into tolerable and intolerable bins based on the risk to people, property, and other factors the program strives to protect. Highway departments are not only concerned with injury to people or damage to vehicles but also anything that affects the flow of traffic and the function of normal highway operations. The movement of travelers, highway workers, and emergency vehicles depends not only on the size of an avalanche but also on the characteristics of the roadway, such as the number of lanes, the average annual daily traffic (AADT), steepness of the grade, associated infrastructure, the location of guardrails and intersections; and the amount of time it takes to recognize an avalanche event occurred, arrange the necessary equipment for snow removal, and return traffic to acceptable flows.

This study uses expert opinion to determine what constitutes a tolerable vs an intolerable event in five avalanche areas with different path characteristics and road configurations across Colorado, USA. This approach closely follows the process forecasters take when determining when and how to mitigate avalanche risk above roadways while at the same time limiting the impact on highway operations. We determined that unlike other metrics commonly used by highway forecast operations, such as avalanche destructive size and avalanche hazard index, expert opinion allows us to take an unconstrained multivariate approach to establish criteria. We discuss how we use this approach to establish goals, understand our performance, and make adjustments to our highway avalanche program.

KEYWORDS: avalanche forecasting, transportation, avalanche hazard

1. INTRODUCTION

Since 1992, the Colorado Department of Transportation (CDOT) and the Colorado Avalanche Information Center (CAIC) have partnered on the Highway Avalanche Safety Program (HASP) for the state and federal highways in Colorado. The HASP includes both forecasting of the avalanche hazard to a roadway and mitigation of that hazard. The primary goal of this programs is to reduce the threat of avalanches to the people who travel in the highway corridors. The program also strives to preserve the movement of people, goods, and services along Colorado's mountain highways.

Either explicitly or implicitly, avalanche safety operations establish risk criteria that inform the hazard reduction effort (IEC/ISO 31010, 2019). This process essentially sorts potential avalanche events into tolerable and intolerable bins based on the risk to people, property, and other factors the program strives to protect (Kaplan and Garrick, 1981; Bründl and Margreth, 2015). Once established, the program operators can implement a strategy to maintain safety and evaluate the program's effectiveness.

Like many transportation groups, HASPs use the avalanche Size - Destructive Force scale D-scale; (American Avalanche Association, 2022). This scale describes the potential damage to a person or vehicle. It is a valuable way of discussing avalanches of various sizes, but it does not take into consideration many of the factors that adversely affect highway function. Schaerer (1989) introduced the avalanche hazard index (AHI), a numerical expression of the damage or loss that could occur from an avalanche impacting a vehicle on a road. The AHI includes the frequency of an encounter and the resulting damage from that encounter. This index is used to characterize, quantify, and compare the hazard from avalanches to various road sections (Armstrong, 1981; Stethem et al., 1994; Mears, 1995; Hendrikx and Owens, 2008). It is a valuable tool for program planning and, at times, evaluation. It accounts for some different avalanche types (e.g., powder snow, sluff, light snow, deep snow, plunging snow) and the intersection of the road and avalanche path. It does not account for how an avalanche would disrupt the traffic flow and function of the road.

Highway departments are not only concerned with injury to people or damage to vehicles but also events that affect the flow of traffic and the function of normal highway operations. The D-scale and AHI are important metrics but do not differentiate between tolerable and intolerable avalanche events. The movement of travelers, highway workers, and emergency vehicles depends not only on the size of an avalanche but how that avalanche disrupts traffic. The disruption can vary depending on the characteristics of the roadway and associated infrastructure, including the number of lanes; the presence of bridges and tunnels; the location of guardrails and intersections; and the amount of time it takes to recognize an avalanche event occurred, arrange the necessary equipment for snow removal, and return traffic to acceptable flows.

We developed an evaluation schema to determine the tolerable impact on highway for individual avalanche paths. We considered how different avalanches affected road function at different locations. Defining tolerable and intolerable events helps us establish program goals, communicate operational needs, and evaluate our mitigation process. We can determine how successful our forecast efforts have been at preventing intolerable events. This paper presents five examples to illustrate this approach and what we have learned.

2. METHODS

We used expert opinion to determine what constitutes a tolerable (Figure 1) and an intolerable (Figure 2) event in five different avalanche paths. Each path had different road configurations, traffic volumes, speeds, and distinct infrastructure characteristics. We list the critical factors considered for each case study. To define an intolerable event, we considered the depth and extent of avalanche debris across the road and how that impacts traffic.

Avalanche extent is described by relative lanes, from not reaching the roadway, white line, center line, to crossing all lanes. The extent descriptors match the data the CAIC forecasters record about individual avalanche events. We considered debris depth in categories relative to the equipment required to clear the roadway or impact on motorists. CAIC forecasters estimate debris depth for individual avalanche events.

We reviewed avalanche occurrence data for six winters beginning in November 2017. We classified avalanche events into tolerable and intolerable events based on the criteria for each path. We used this data to review the HASP's efforts in each path. Our case studies highlight successes and illustrate where improvements can be made.

Figure 1. An example of small avalanches running into the inside lane. In areas with lower traffic volumes and slower speeds, drivers can navigate avalanches like these by taking turns driving in the open lane. Events like this can, however, slow or stop traffic under other large avalanche paths which may be an intolerable situation in some areas.

Figure 2. An example of an intolerable event. Large avalanches can require heavy equipment to clear the debris from the roadway, resulting in unusually long closure times that can quickly cause traffic delays and loss of revenue.

3. CASE STUDIES

3.1 Sister 3 - US 6, Loveland Pass

US 6 over Loveland Pass is a major east-west route. It is the hazardous material and alternate route for Interstate 70 through the Eisenhower-Johnson Memorial Tunnel. The route provides access from major cities to several ski areas. Sister 3 is one of ten avalanche paths on this section of highway. Sister 3 plunges steeply to the highway. There is no shoulder, and small avalanches can easily put debris more than two feet deep on the inside lane of the highway. In 2014, due to the increasing volume of traffic and the amount of mitigation required to keep this section of US 6 open, CDOT installed a series of remote avalanche control systems (RACS) in the start zones.

AADT	1700	**Truck Traffic**	20%
Posted Speed	40 mph	**Highway Location**	Track

Critical Factors to Establish Risk Criteria: Two lane road with no shoulders; no guardrails; paths plunge steeply onto the road; paths are steep so small avalanches can pile up in the inside lane; CDOT patrols cycle about every 30 minutes; standing traffic is under other large avalanche paths.

Intolerable Event Criteria: Any avalanche that puts more than 1 foot of debris in the outside lane causing traffic to back up under other large avalanche paths in the area. Any delay that results in more than 20 minutes of stationary traffic.

We reviewed data for 77 unique events where avalanches impacted the roadway during the six-year study period. We determined that 43 (56%) of the events were tolerable. Avalanche debris was confined to the inside lane with less than a foot of debris covering the outside lane. Traffic could continue to pass even if speeds were slowed, and except on weekends and high volume times, traffic would not stand under the other avalanche paths in the area. We determined that 33 (44%) of the events constituted intolerable events (Figure 3): Avalanche debris was deeper than a foot in the outside lane, or both lanes were covered by avalanche debris. Only one of the intolerable events was due to a natural avalanche.

Figure 3. Small avalanches in areas where the avalanche path plunges to the road can easily put debris in the outside lane constituting an intolerable event.

Based on this data, we are doing a good job when it comes to forecasting and preventing intolerable natural avalanches. We only had no results during mitigation missions 8% of the time, so we are timing mitigation well. Avalanche mitigation is effective in Sister 3, although we may be able to decrease the number of missions and still achieve our programmatic goals.

Our analysis does not account for the timing of storms. We typically perform active mitigation in the early morning hours, to avoid high traffic periods. If we are concerned about heavy snowfall in the afternoon, we may shoot in the morning and release a smaller avalanche. Similarlly, we may shoot on a Thursday if we are worried about the hazard rising over the upcoming weekend. Loveland Pass often closes for hazardous weather conditions before preventative avalanche closures are necessary. Mitigation is often carried out during these closures or before sunrise, reducing the impact of avalanches because the road is already closed or traffic volumes are low. Our analysis does not accout for the effects of these situations on the size of avalanches that reach the highway.

3.2 Scottys Curve - US 6, Loveland Pass

Scottys Curve is a small avalanche path above the east-bound lane of US Highway 6, near the top of Loveland Pass.

AADT	1700	**Truck Traffic**	20%
Posted Speed	40 mph	**Highway Location**	Track

Critical Factors to Establish Risk Criteria: Two lane road with no shoulders; no guardrails; traffic speeds are often slow because of steep grades and the winding road; steep dropoff on the downhill side of the path; the path is short and does not produce many large (≥D2) avalanches.

Intolerable Event Criteria: Due to the slow speeds and size of the avalanche path, we determined that an avalanche would have to be deeper than about two feet and cross all lanes to be an intolerable event. An avalanche of this depth and size could potentially sweep a vehicle off the roadway resulting in a catastrophic accident.

We recorded 15 explosive-triggered avalanches in the Scottys Curve avalanche path in the six winters constituting this study. None of the recorded events were natural avalanches. Only one was an intolerable event that occurred during a 100-year avalanche cycle in March 2019. Ninety-three percent of the avalanches in the Scottys Curve met the criteria for tolerable events.

Based on this data, we are doing a very good job controlling natural avalanches in Scottys Curve. All the mitigation missions produced avalanches, so we seem to be timing the missions well. However, in 6 (40%), we triggered avalanches that either stopped on the inside shoulder or did not put any debris on the centerline of the roadway. That indicates that we may be able to decrease the number of missions in Scottys Curve and still achieve our operational goals.

3.3 Bethel - Interstate 70, East Eisenhower Johnson Memorial Tunnel

Interstate 70 is the major east-west route across Colorado. There are only a handful of mapped avalanche paths that affect the interstate. Bethel is a large, southeast-facing avalanche path two and a half miles east of the Tunnel above the westbound lanes (Figure 4).

AADT	38,000	**Truck Traffic**	10%
Posted Speed	65 mph	**Highway Location**	Runout

Critical Factors to Establish Risk Criteria: Four lane divided highway; large path; starts in the alpine; and run over 1000 vertical feet to the Interstate in the valley bottom; traffic can often back up underneath the Bethel slide path especially during treacherous winter driving conditions; avalanches infrequently reach the Interstate, most stop in the track or are contained by diversion berms.

Intolerable Event Criteria: Due to the traffic volume, traffic speeds, and potential waiting vehicles (Figure 5), any debris or powder cloud reaching the interstate constitutes an intolerable event (Figure 6).

We recorded 12 avalanche events in Bethel during the study period. We classified 3 (25%) events as intolerable. In 2017, a natural avalanche caused a powder cloud to cover traffic that was stopped under the path. In 2023, the powder cloud from a natural avalanche swept over the interstate at 1:00 AM. During the historic 2019 avalanche cycle, a helicopter mitigation mission while the Interstate was closed triggered a very large avalanche that covered the entire interstate and destroyed the wire rope safety barrier dividing east and west bound lanes.

We classified 9 (75%) of the avalanches as tolerable events. Three of those were natural avalanches. The other seven occurred during mitigation missions. During mitigation, 60% of the deployed explosives resulted in no avalanche release. It is often impossible to carry out mitigation missions during peak instability due to the constraints of closing the busiest Interstate in Colorado. Our data indicates that we could do more mitigation during peak instability, trying to trigger smaller avalanches and reduce the potential for large avalanches and powder clouds to reach the Interstate.

Figure 4. Interstate 70 crosses through the runout zone of the Bethel slide path.

Figure 5. Stationary traffic can quickly lead to a dangerous situation if it backs up under unmitigated avalanche paths. Image courtesy of Peter M. Fredin

Figure 6. An avalanche in the Bethel path crosses Interstate 70. This avalanche occurred at 11:40 AM on 17, January, 2017. Solid debris from the slide stopped uphill of the roadway, but given the travel speeds and number of vehicles, any impact from an avalanche is unacceptable Image courtesy of Doug Evans Photography

3.4 Big Slide - US 50, Monarch Pass

US 50 is an east-west route cutting through the heart of Colorado. Big Slide is a relatively small avalanche path east of the summit and about one mile east of Monarch Mountain ski area. Big Slide begins in trees and drops down a steep cutbank to the highway. There are two westbound ascending lanes on the inside of the highway and one lane descending on the outside. CDOT installed a series of Gazex exploders in the start zone of Big Slide in 2019.

AADT	2400	**Truck Traffic**	13%
Posted Speed	45 mph	**Highway Location**	Track

Critical Factors to Establish Risk Criteria: Fairly small path; no guardrail on the downhill side; due to the remote location it can take a significant amount of time to remove avalanche debris; closures adversely affect Monarch Mountain ski area; it takes a large avalanche to cover all of the lanes and would take a substantial-sized avalanche to knock a vehicle off the road; small avalanches can back traffic up under other avalanche paths, however, those paths are small and avalanches would be unlikely to injure a person inside a vehicle.

Intolerable Event Criteria: Any avalanche large enough to cover both uphill lanes or cross the centerline into the outside lane is an intolerable event. Avalanches less than about two feet deep blocking just the inside lane of traffic are tolerable events.

We reviewed data for 50 unique events where avalanches impacted the roadway. Debris crossed the centerline and was deeper than about two feet, constituting an intolerable event, 30 (60%) times. All of the intolerable events were triggered by explosive mitigation. We determined that 20 (40%) of the avalanches were tolerable events. Traffic was slowed but could continue up the pass and did not back up below other avalanche paths.

Our data indicates success in forecasting and preventing intolerable natural avalanche events. We are triggering too many intolerable avalanches during mitigation, resulting in extended closures. We could conduct mitigation more frequently to try to keep avalanches

smaller and easier to clean up. We should note that some of the largest intolerable avalanches were triggered prior to the installation of the Gazflex system.

3.5 Stud Muffin - US 160, Wolf Creek Pass

US Highway 160 is the main east-west route in southern Colorado. Stud Muffin is a narrow avalanche path five miles southwest of Wolf Creek Pass. The path begins in a rocky gully 250 vertical feet above the highway. Mark Mueller, the original CAIC forecaster for Wolf Creek Pass, called Stud Muffin a “nuisance path.” It does not produce a lot of large avalanches, but it produces more avalanches to the highway than any other path on Wolf Creek Pass. In 2019, CDOT installed an Obellx exploder in the start zone.

AADT	3700	**Truck Traffic**	10.5%
Posted Speed	35 mph	**Highway Location**	Track

Critical Factors to Establish Risk Criteria: The path plunges onto the highway above the single downhill westbound lane; there is a substantial shoulder on the inside of the highway; there are two ascending, eastbound lanes; no guard rail above a steep drop; the speed limit is 35 miles per hour below Stud Muffin, and uphill truck traffic is often moving much slower.

Intolerable Event Criteria: Any avalanche that results in more than a half-foot of debris across either of the outside lanes is an intolerable event. A vehicle that loses traction in avalanche debris while traveling uphill can disrupt traffic for an extended period of time, and cause traffic to back up under larger adjacent avalanche paths.

There were six events during the study period where avalanche debris impacted the highway. There were 4 (66%) intolerable events where avalanche debris crossed the centerline. All of these events were explosive-triggered avalanches. The data shows that we are mitigating natural avalanches in this path well. The avalanche size makes it unlikely for a vehicle to be pushed off the road. However, we need to limit the potential for avalanches that slow or stop traffic under adjacent avalanche paths.

4. CONCLUSIONS

Using avalanche size to create our risk critera for the HASP did not allow us to include many issues that are important to the flow of traffic and function of the highway. This multifactor appoach essentally takes issues that we often discuss, and put them into an explict framework for each avalanche path that threatens the roadway. It helps both forecasters and maintenace workers discuss potential events, set thresholds, track, and schedule mitigation missions. It provides a framework for communication between employees and supervisors.

In the future we plan to improve our data collection to support better evaluation of the program. Two areas for improvement are natural avalanche activity and multiday events where mitigation missions are driven by forecast traffic volumn more than avalanche hazard.

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