FINAL REPORT **WYDOT WY-18/03F**

A Comprehensive Technology Assessment for Highway Avalanche Hazard Management: 'Choosing the Right Tool for the Job'

Rand Decker, Ph.D., Principal Investigator
83 El Camino Tesoros,
Sedona, Arizona 86336
(928) 202-8156
randdecker@aol.com

Disclaimer Notice

This document is disseminated under the sponsorship of the Wyoming Department of Transportation (WYDOT) in the interest of information exchange. WYDOT assumes no liability for the use of the information contained in this document. WYDOT does not endorse products or manufacturers. Trademarks or manufacturers' names appear in this report only because they are considered essential to the objective of the document.

Quality Assurance Statement

WYDOT provides high-quality information to serve Government, industry, and the public in a manner that promotes public understanding. Standards and policies are used to ensure and maximize the quality, objectivity, utility, and integrity of its information. WYDOT periodically reviews quality issues and adjusts its programs and processes to ensure continuous quality improvement.

Quality Assurance Statement

WYDOT provides high-quality information to serve Government, industry, and the public in a manner that promotes public understanding. Standards and policies are used to ensure and maximize the quality, objectivity, utility, and integrity of its information. WYDOT periodically reviews quality issues and adjusts its programs and processes to ensure continuous quality improvement.

Copyright

No copyrighted material, except that which falls under the "fair use" clause, may be incorporated into a report without permission from the copyright owner, if the copyright owner requires such. Prior use of the material in a WYDOT or governmental publication does not necessarily constitute permission to use it in a later publication.

- Courtesy: Acknowledgment or credit will be given by footnote, bibliographic reference, or a statement in the text for use of material contributed or assistance provided, even when a copyright notice is not applicable.

- Caveat for Unpublished Work: Some material may be protected under common law or equity even though no copyright notice is displayed on the material. Credit will be given and permission will be obtained as appropriate.

- Proprietary Information: To avoid restrictions on the availability of reports, proprietary information will not be included in reports, unless it is critical to the understanding of a report and prior approval is received from WYDOT. Reports containing such proprietary information will contain a statement on the Technical Report Documentation Page restricting availability of the report.

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
WY-18/03F		

4. Title and Subtitle	**5. Report Date**
A Comprehensive Technology Assessment for Highway Avalanche Hazard Management: Choosing the Right Tool for the Job	December 2017
	6. Performing Organization Code:
7. Author(s) Rand Decker (ORCID: 0000-0002-5487-1392)	**8. Performing Organization Report No.**
9. Performing Organization Name and Address Rand Decker, Sole Proprietor 83 El Camino Tesoros, Sedona, Arizona 86336 (928)202-8156, randdecker@aol.com	**10. Work Unit No.** **11. Contract or Grant No.** RS06-211
12. Sponsoring Agency Name and Address Wyoming Department of Transportation 5300 Bishop Blvd Cheyenne, WY 82009-3340 WYDOT Research Center (307)777-4182	**13. Type of Report and Period** Final Report **14. Sponsoring Agency Code** WYDOT

15. Supplementary Notes
This research was conducted in cooperation with the Wyoming Department of Transportation's Research Center.

16. Abstract: There are a dozen different technologies that can be naturally sub-divided into two very different avalanche control and defense paradigms that can be used to manage avalanche hazards on mountain highways: active avalanche control and passive/constructed avalanche defense. The Wyoming Department of Transportation's (WYDOT) avalanche control and defense program in and around Jackson, Wyoming, utilizes five different active avalanche control technologies and one passive/constructed deployment of snow supporting structures. In this report, metrics of cost for these avalanche control and defense technologies are analyzed. The seasonal cost of WYDOT's avalanche control and defense program rose from $97,000 in 2008/09 to $172,000 by 2015/16, largely in response to investment in modern active control and passive/constructed avalanche defense. As a consequence, traffic delays have been reduced, as have reliance on the military howitzer for active avalanche control. Traffic delays can be further reduced through investment in high capacity avalanche debris cleanup capabilities. As the seasonal costs for WYDOT's avalanche control and defense program have grown, the percent fraction of these program costs for personnel has declined. There is a margin to improve capacity building and professional development of existing and future WYDOT avalanche control personnel. In large part to free up WYDOT active avalanche control personnel to focus on State Route 22, on Teton Pass, it is recommended that US Route 189/191, in Hoback Canyon, be defended in the future with snow-net snow supporting structures. State Route 22 on Teton Pass is poised to become a state-of-the-art active avalanche control program, and needs to be. Despite the successful reduction in its use, the military weapon component of WYDOT's active avalanche control program provides low cost redundancy and should be maintained in reserve. There are traffic delays from avalanche control of two different durations, short delays of an hour or less, and much more uncommon delays of several hours or more. Long duration traffic delay for avalanche control can be managed to further reduce its impacts on motorists.

17. Key Words	**18. Distribution Statement**
Wyoming, WYDOT, Technology, Assessment, Avalanche, Avalanche Control, Active Control, Passive/Constructed Defense, Traffic Delay, Costs, Transportation, Highway, State Route 22, Teton Pass, US Route 189/191, Hoback Canyon, US Route 89, Snake River Canyon, Snow Shed, Snow Gallery, Snow Bridges, Snow Rake, Hand Charge, Heli-bombing, Military Weapon, Howitzer, Avalanche Guard, GAZEX®, TAS O'Bellx®	This document is available through the National Transportation Library and the Wyoming State Library.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	70	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized.

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

Source: Turner-Fairbank Highway Research Center R&D

Table of Contents

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

ADT – Average Daily Traffic
BATF- Bureau of Alcohol, Tobacco, and Firearms
CalTrans – California Transportation (Department)
CATEX® – Cableway for Transporting Explosives
CDOT - Colorado Department of Transportation
DOT – Department of Transportation
FHWA – Federal Highway Administration
IDT – Idaho Transportation Department
RAC - (WYDOT) Research Advisory Committee
RM – Reference Marker
NCHRP ITS IDEA - National Cooperative Highway Research Program Intelligent Transportation System Innovative Development Awards
NEPA – National Environmental Policy Act
NOAA Snotel – National Oceanographic and Atmospheric Administration Snow Telemetry (report system)
SWE – Snow Water Equivalent
TAS - Technologle Alpine de Securite
TRB – Transportation Research Board
WYDOT- Wyoming Department of Transportation

CHAPTER 1: EXECUTIVE SUMMARY

When it comes to managing avalanche hazards, there is no one right choice or answer for all the avalanches that threaten highways and alpine infrastructure. There are a dozen different technologies that can be naturally sub-divided into two very different avalanche control and defense paradigms that can be used to manage avalanche hazards on mountain highways. Active avalanche control involves forecasting the propensity for avalanching to occur based on winter storm severity and characteristics, and prevailing snowpack conditions, and then pro-actively attempting to release the threatening avalanches with various shock sources, and shock delivery systems while the highway is temporarily closed. Passive/constructed avalanche defense is just that; engineered and constructed facilities in the avalanche starting zone that supports the snowpack in-place and precludes the onset of avalanching, and artificial avalanche tunnels, commonly known as avalanche sheds or galleries, which pass any avalanche that may occur on its own, naturally, over the highway. Active avalanche control is personnel intensive and results in traffic delays to implement. Passive/constructed avalanche defense does not require personnel to defend from avalanches, and is between 10 and 1000 times more expensive than active avalanche control to implement.

Today, WYDOT's avalanche control and defense programs in and around Jackson, Wyoming, utilize five different active avalanche control technologies on US Route 189/191, in Hoback Canyon, and State Route 22, on Teton Pass, and one passive/constructed deployment of snow supporting structures in the highway reference marker (RM) 151 Avalanche-starting zone, above US Route 189/191, south of Jackson, Wyoming. These are not the only avalanche control and defense technologies ever utilized or researched by WYDOT. In 1968, an attempt was made to span the Glory Bowl avalanche runout zone on State Route 22, on Teton Pass, with a traditional steel frame bridge. The Crater Lake Bridge was lost to an avalanche before it could be completed [Yount, 2016].

In a little known fact about WYDOT's avalanche control and defense program, passive/ constructed defense was the first successful avalanche control or defense technology of any kind implemented by WYDOT. During the realignment of US Route 189/191, in Hoback Canyon, planned in 1968 and completed in 1970, avalanche barrier mounds and deflection dams were constructed for the "Bull-of-the-Woods" avalanche runout zone to slow any avalanche that might get started and hopefully keep it from reaching the highway below [FHWA, 1968]. The "Bull-of-the-Woods" avalanche is a large, uncontrolled avalanche just east of the "Cow-of-the-Woods" and "Calf-of-the-Woods" avalanches in Hoback Canyon. Because of the highway realignment, it no longer threatens US Route 189/191, though it continues to avalanche regularly. These avalanche defense barriers and dam can still be seen today in the bottom of the large side-valley, on the south side of the Hoback River, east of the "Cow-of-the-Woods" avalanche on US Route 189/191.

By 1972, WYDOT maintained an operational avalanche control and defense program for the highways in and around Jackson [Yount, 2016], that included the first implementation of both military weapons and an "early generation Avalauncher® (that) was used for targets on Twin Slides" [Yount, 2016]. The Twin Slides avalanches are also on State Route 22 in Teton Pass.

WYDOT has an earned reputation for trying, and being the first to try, multiple different novel avalanche control and defense technologies in an effort to improve their own program, and others, where possible. This is due in large part to three elements:

- WYDOT Research Advisory Committee (RAC) project champions that arose from WYDOT's District 3 technical and operational leadership.
- The 'on the ground' assistance of WYDOT avalanche program personnel in the Jackson Maintenance facility.
- The assistance and, ultimately, the financial support of WYDOT's Research Center in Cheyenne.

Of these efforts, some were clearly successful in moving new methods and technologies into WYDOT's avalanche control and defense program, particularly the O'Bellx® portable gas exploder in Hoback Canyon, and the passive/constructed snow supporting defense structures in south Jackson. To be complete and accurate, there were also research and technology implementation trials that did not lead to widespread implementation in WYDOT's avalanche control and defense program. More often than not, those projects that lead to negative results were as valuable in pointing towards alternative technologies to investigate, as they were setbacks.

This includes the NCHRP ITS-IDEA and follow-on multi-state, including the WYDOT Research Center and its RAC, pooled fund studies into automated avalanche detection and alarm systems in the late 1990's [Rice, 2000; Rice, 2002; Decker, 2003]. In a similar guise, WYDOT also supported an investigation into the use the low frequency infrasonic 'rumble' as an avalanche detection technology [Yount, 2008].

Nonetheless, the use of automated avalanche detection and alarm systems for knowledge based and real time avalanche security actions, such as highway and rail corridor closures, was an idea before its time. It has now become a standard of practice in Europe [Ulivieri, 2012, Meier, 2016]. During an avalanche cycle on January 22, 2018, their avalanche detection and alarm system implemented an automated closure of the short, but critical and high volume rail line into Zermatt, Switzerland.

The other noteworthy WYDOT Research Center/RAC supported avalanche defense technology trial that did not lead to widespread implementation was the Snow Sail project on the RM 151 Avalanche above US Route 189/191, in south Jackson. An attempt was made to 'passively' defend US Route 189/191 from the RM 151 Avalanche with a deployment of 'snow sails' - low cost, light weight, hand constructed panels of fabric used to cause the wind flowing around them to roughen the avalanche slope and, theoretically, preclude avalanche fracturing and avalanching [Yount, 2004(a); Yount, 2004(b)]. Though very inexpensive, they did not work. On January 1, 2004, after the snow sails had been in service of three seasons, the RM 151 Avalanche came onto an open US Route 189/191. The decision to explore the use of passive/constructed snow supporting structures for avalanche defense in the starting zone of the RM 151 Avalanche began at this time. The subsequent feasibility and 65 percent preliminary design of the successful RM 151 snow supporting structural avalanche defense was supported by the WYDOT Research Center and its RAC with project champions from WYDOT's District 3.

The research being report here has attempted a generic, broadly applicable, structured process to aid in the choice of avalanche control and defense technology for a given highway application. Metrics of cost for the avalanche control and defense technologies presently implemented by WYDOT include the following:

- The cost of avalanche control and defense technology procurement, installation, and rehabilitation.
- Personnel costs associated with the operation of each technology.
- Avalanche control, defense technology operating, and maintenance costs.
- The duration of travel delays resulting from active avalanche control.

Data from WYDOT's avalanche control and defense program in Jackson, Wyoming, were analyzed for nine winter seasons, 2008/2009 through 2016/2017, to examine the distribution of these costs over this period. The number of active avalanche control shots fired by each technology, and the cost per shot or round was evaluated. Further, the impact these technologies and their recent modernization have had on traffic delays on State Route 22, on Teton Pass, and on US Route 189/191, in Hoback Canyon, were evaluated.

The total seasonal cost of WYDOT's avalanche control and defense program rose from $97,000, in the 2008/2009 season, to $135,000 by the 2012/2013 season. During the 2012/2013 season, passive/constructed snow supporting structures were implemented at the RM 151 Avalanche starting zone, on US Route 189/191, south of Jackson, Wyoming, at a cost of $2.8 million, including design and on-site construction inspection. The contractor's cost, including materials, fabrication, transport to site, erection, and restoration, was $2.3 million. A practical 60-year service life for this passive/constructed avalanche defense facility has effectively added $46,000 annually to WYDOT's avalanche control and defense costs over the next 55 years. Starting in the 2012/2013 season, this annualized passive/constructed avalanche defense cost increased the seasonal cost of WYDOT's avalanche control and defense program to $135,000. In the 2013/2014 season, and again in the 2015/2016 season, one-time capital investments were made in modern active avalanche control technology and the rehabilitation of existing technologies. These expenditures were successfully absorbed in the annual budgets for the 2013 and 2016 budget years. The result is the seasonal cost of WYDOT's avalanche control and defense program rose to $172,000 by the 2015/2016 season. The 2016/2017 season was an uncommonly severe winter and seasonal costs jumped to $196,000 in response to that external force. The value in having experienced the extreme winter of the 2016/2017 season is discussed further in this report.

To see a visual representation of the cost distributions discussed above, please see Figures 35 through 42. These are the cost distributions for all active control and defense technologies, and personnel costs for the 2008/2009 through the 2016/2017 seasons. Note that starting in the 2012/2013 season, these costs are differentiated by each individual avalanche control or defense technology found in use in WYDOT's avalanche control and defense program.

As a fraction of these total costs, the personnel costs in WYDOT's avalanche control and defense program grew much more modestly, from an average of $66,000 annually over the 2008/2009 through 2011/2012 seasons, to just over $70,000 by the 2015/2016 season. For the extraordinary winter of 2016/2017, personnel costs jumped to $75,000. As total seasonal costs for WYDOT's avalanche control and defense program have grown, the percent fraction of these costs for personnel has declined.

Based on an analysis of personnel costs, cost per shot for active avalanche control, the costs to implement passive/constructed avalanche defense, and the impact of modernization and rehabilitation of active avalanche control on traffic delays, the following recommendations are made.

1. State Route 22, on Teton Pass, and US Route 189/191, in Hoback Canyon:

State Route 22, on Teton Pass, enjoys an effective active avalanche control program that is poised to become state-of-the-art, and it needs to be. State Route 22, on Teton Pass, carries an average of 4,430 vehicles, measured by an Average Daily Traffic (ADT) count, during the winter months [ITD, 2016]. A large fraction of these vehicles are regular commuters that have a high degree of awareness and coordinated interaction with the traffic delays that results from active avalanche control. Recreationalists use Teton Pass to access the backcountry, including terrain that threatens State Route 22 with their avalanches. There is no tractor-trailer traffic allowed on State Route 22 in the winter months, as such, commercial vehicles are not a significant factor.

The implementation of passive/constructed avalanche defense for State Route 22, on Teton Pass would be either snow supporting structures in the avalanche starting zones, and/or avalanche galleries or sheds at the highway. Environmental issues, including visual assets, may preclude the use of constructed facilities in these starting zones. By virtue of the number and size of the avalanche starting zones, and the length of State Route 22 impacted by avalanche debris, the cost to implement some combination of snow supporting structures and avalanche sheds on Teton Pass is estimated at between $80 million to $120 million. It's hard not to notice that with existing infrastructure and personnel, and their costs, successful active avalanche control on State Route 22, on Teton Pass, can be conducted for another 500 years for the same cost as a one-time investment of $100 million in passive/constructed avalanche defense.

A modern, state-of-the-art active avalanche control program on State Route 22, on Teton Pass, should lead to further reductions in traffic delay. Traffic delay is the sum of both the active avalanche control mission and the subsequent cleanup of avalanche debris from the highway. Investment in big/fast avalanche debris cleanup equipment should keep pace with that of modern active avalanche control technology.

A state-of-the-art active avalanche control program on State Route 22, on Teton Pass, would require a dedicated team of active avalanche control personnel that focus only on that site. If WYDOT's existing active avalanche control personnel's sole responsibility was to monitor and actively control avalanches on State Route 22, on Teton Pass, it would be fully deployed. Presently, WYDOT's avalanche control personnel are asked, simultaneously, to address US Route 189/191, in Hoback Canyon, and State Route 22, on Teton Pass, when both are at risk of avalanching, and in need of timely and personnel intensive active avalanche control efforts. This stretches this workforce thin. One alternative is to increase the number of active avalanche control personnel.

As an alternative to increasing personnel strength, US Route 189/191, in Hoback Canyon, can be defended with a deployment of passive/constructed modern, lightweight, flexible snow-net snow supporting structures (see Figure 24). The “Cow-of-the-Woods” and “Calf-of-the-Woods” avalanche starting zones, which are about nine miles south of Jackson, Wyoming, along US Route 189/191, are small, on the order of one to two acres combined. The cost to implement snow-net passive/constructed avalanche defense in these starting zones is estimated at $2.8 million. This was the same cost for passive/constructed avalanche defense on the RM 151 Avalanche starting zone, on US Route 189/191, south of Jackson, Wyoming.

Investment in passive/constructed snow-net snow supporting structures in the “Cow-of-the-Woods” and “Calf-of-the-Woods” avalanche zone on US Route 189/191, in Hoback Canyon, would increase WYDOT’s seasonal costs for avalanche control and defense by $40,000 to $45,000 annually, over the estimated 60-year service life of this avalanche defense technology. This would be a 25 percent increase in total seasonal avalanche control and defense costs. Without any other large capital expenditures or increases to personnel during the period, a capital investment in passive/constructed avalanche defense for US Route 189/191, in Hoback Canyon, would bring WYDOT’s seasonal costs for avalanche control and defense up to an estimated $225,000 for the near and foreseeable future. Upon implementation of passive/constructed snow-net supporting structures in Hoback Canyon, $300,000 of these costs can be recovered immediately by moving the active avalanche control Technologle Alpine de Securite (TAS) O’Bellx® portable gas exploders presently found in Hoback Canyon to State Route 22, on Teton Pass.

What passive/constructed snow-net snow supporting structures on US Route 189/191, in Hoback Canyon, do best for WYDOT is to make State Route 22, on Teton Pass the primary focus of WYDOT’s effective active avalanche control program, with the goal of improving upon it further, including continued reductions in traffic delay.

2. The reduction in military weapon use:

A reduction in the use of the military weapon as the first technology of choice for WYDOT’s avalanche control and defense program has been accomplished through the introduction of modern fix and portable gas exploders, and civilian ‘mortars’. Nevertheless, the military howitzer weapon component of WYDOT’s active avalanche control program should be maintained in reserve. It provides low cost redundancy in the event that the existing avalanche control technologies, in particular on State Route 22, on Teton Pass, were to become inoperable. The present supply of ammunition for the howitzer is estimated at 50 percent of the ammunition bunker’s capacity [Gorsage, 2018]. This supply should be replenished and maintained at or near full.

The annual inspection, maintenance, and personnel costs to remain proficient as military weapon operators for active avalanche control are modest, and are present in the existing budget. Maintaining the proficiency of WYDOT’s avalanche control personnel as military weapons operators includes the annual training/re-training workshop and military liaison briefing required of all avalanche control personnel that operate military weapons for this purpose. Attendance at this annual Avalanche Artillery Users of North America Committee (AAUNAC) meeting [Abromeit, 2004] is one of only a few and a preeminent professional development opportunity for active avalanche control personnel, WYDOT's included.

3. Short and long duration traffic delay:

The typical traffic delay on State Route 22, on Teton Pass, and on US Route 189/191, in Hoback Canyon, due to WYDOT's active avalanche control program, is short, 30 minutes to an hour [Yount, 2016]. Long duration delays that can last hours are uncommon but occur with enough regularity that motorist information, and alternative queuing and lay-up sites should be investigated that include the motorists' last opportunities to stop where there are roadside services.

4. Capacity building and professional development of avalanche control personnel:

There is a margin available for improving both capacity building and professional development opportunities for WYDOT's cohort of existing and future active avalanche control personnel.

CHAPTER 2. PROBLEM STATEMENT

There is always a challenge in picking the right tool for the job, especially when more than one will do. These are our choices, and their outcomes are usually costly up-front, and difficult and costly to change later. Therefore, we are encouraged to get it as close to right the first time as we can, especially if we are trying something new. This is not always obvious or easy.

In this vein, there is no one right choice or answer for all the avalanches that threaten highways and alpine infrastructure. Because of the differences in each avalanche and its control challenges, one technology might be better above a mountain highways here in the United States, but not in another part of the world, say to protect a hydropower surface station in China. It is these differences that have led to the development of such an extensive array of avalanche control and defense technologies. Of the avalanche control and defense technologies to choose from, they all do at least one of the following:

- Support the snowpack in place, precluding the elastic fracturing failure of the snowpack that leads to avalanches.
- Commute the offending avalanche over or around the people and property that you are trying to protect.
- Cause the avalanches to come down when you think you will be able to, and everything at risk below has been moved out of harm's way or buttoned down for the duration of active avalanche control activities.

There are a dozen different methods and technologies that can be naturally sub-divided into two very different avalanche control and defense paradigms that can be used to manage avalanche hazards on mountain highways. These avalanche control and defense technologies are used to protect highway and other ground transportation facilities worldwide. Many of these are found in practice or have been attempted in WYDOT's avalanche control and defense program, in and around Jackson, Wyoming.

This research has attempted a generic, broadly applicable, structured process to aid in the choice of avalanche control and defense technology for a given highway application, including an assessment of the state-of-the-art TAS O'Bellx® portable gas exploder, a the remotely fired gas exploder used for active avalanche control.

CHAPTER 3. PROJECT BACKGROUND

The consequences of snow avalanche hazard and delay on mountain highways in winter climates, including the western United States, are the potential for injury, loss-of-life, property damage, and the direct and indirect cost of traffic delay. Depending on the avalanche control and defense technology chosen, significant Department of Transportation (DOT) personnel resources may be required, often during severe winter storms, when this resource is at a premium.

There are numerous avalanche control and defense technologies available to domestic DOTs for this purpose. As noted in Chapter 2, avalanche control and defense technologies can be divided into two effective, but otherwise very different categories.

- **Active avalanche control** includes the sum of both proactively forecasting those periods when the propensity for dangerous avalanching onto a highway is high, and then actively controlling those avalanches, while the highway is closed and secured of people and vehicles. Active avalanche control involves forecasting the propensity for avalanching to occur based on winter storm severity and characteristics, and prevailing snowpack conditions, and then pro-actively attempting to release the threatening avalanches with various shock sources and shock delivery systems while the highway is temporarily closed. Active avalanche control gets its name not just from the resulting avalanche activity, but also from active DOT personnel. Active avalanche control is personnel intensive. Both the forecasting and control phases of active avalanche control require DOT personnel to be engaged, most often as teams, in real time, to be effective.

- **Passive/constructed avalanche defense** is just that; engineered and constructed facilities in the avalanche starting zone that supports the snowpack in-place and precludes the onset of avalanching, and artificial avalanche tunnels, commonly known as avalanche sheds or galleries, that pass any avalanche that may occur naturally on its own over the highway. As the term implies, passive/constructed avalanche defense does not require DOT personnel to be actively engaged during severe winter storms for this technology to be effective in defending the highway from avalanches.

The paradigm difference that underpins these two overarching categories of avalanche control and defense is glaring. Active control seeks proactively to cause avalanches when you think you can exercise some control over them. The safest highway during periods of high avalanche propensity is a closed highway. Under the paradigm of active avalanche control, the second safest state for a highway is one covered in debris from a very recent, pro-actively released avalanche. This requires embracing the premise that once a specific avalanche has been brought down, it is unlikely to avalanche again in the very near future, despite the fact that it will avalanche again at some more distant time in the future. So, if DOTs can forecast for, and then cause the offending avalanche to release and come down onto the highway while the highway is temporarily closed, the DOT can then cleanup the debris and reopen. This requires intensive human intervention and activity. Active control leads to avalanching, in most cases onto the highway, and the requirement for a subsequent mechanized cleanup of the avalanche debris prior to reopening the highway.

There is one other pre-requisite for successful active avalanche control. One must be able to shake the avalanche-starting zone with enough force to cause the avalanche to release. The methods for producing these avalanche releasing shocks includes chemical and gas explosions, and explosive military ordinance. Since these shocks need to occur in the avalanche starting zones in the highest reaches of the mountains, there are technologies that will launch or shoot the explosives into the avalanche starting zone from a secure and almost invariably lower position. There are also technologies for delivering either the explosive charge or an explosion of mixed combustible gases that can be permanently fixed in the avalanche starting zone or deployed there with a helicopter that can then be remotely fired from secure positions.

Passive/constructed avalanche defense embraces just the opposite paradigm, and includes construct facilities that either hold the snowpack in place, precluding the onset of avalanching in the first place, regardless of how much these avalanche would like to come down, and facilities that allow avalanches that have started all on their own to pass over the highway, even though motorists may be on the highway at the very instant the avalanche is passing overhead. It is passive in that there are no more avalanches than what nature would send down on her own. No one is out there actively forcing avalanches to release. It is passive in that it does not take significant personnel resources to perform its job during dangerous periods of high avalanche propensity and activity. One does not even have to forecast for periods of high avalanche propensity. It is either not going to avalanche or the ones that do are free to do so without net harm to the highway and its users. There is no cleanup of avalanche debris from the highway required. Passive/constructed avalanche defense is just that - defensive. It accepts that either the snowpack has to be supported in the starting zone so it will not avalanche in the first place, or avalanches from unsupported snowpack are inevitable, and will be defended against with an avalanche shed at the highway, allowing the avalanche to pass over the affected highway section.

Set out this way, it might seem that passive/constructed avalanche defense would trump active avalanche control as the method of choice for most highway avalanche control and defense applications. This would have been true long ago, if it were not for the sheer number of avalanches that threaten highways, many that are on rural low volume highways, and the fact that capitalization of passive/constructed avalanche defense technology is typically between 10 and 1000 times more expensive than managing the same avalanche with active control.

3.1. Avalanche forecasting and active control

The art and science of forecasting the propensity for avalanches to occur is a well developed and well documented methodology, having been pioneered and practice in the United States and Canada for over 60 years [Perla, 1972]. It is a personnel intensive activity requiring learned skills in both the technical fields of transportation, snow and cold regions, and winter mountaineering. Even though the avalanche forecasting skill set is widely applicable, it can often take several years to develop proficiency and expertise with the nuances of a specific region.

Avalanche forecasting and active control is practiced by transportation agencies, communities, ski areas, regional public service entities for recreational backcountry users, mining companies, and railroads in both North America and Europe, amongst others. In almost every instance where an avalanche hazard forecast for a highway corridor indicates a high propensity for avalanches, there are pro-active actions taken by DOT personnel to reduce the exposure of motorists to this evolving hazard. The simplest action is to close the affected highway until the avalanche hazard subsides. These delays can last days to weeks. Alternatively, pro-active action can be taken to release or bring down the offending avalanches while the highway is temporarily closed, working from the premise that once it has avalanched that particular avalanche path is unlikely to avalanche again until the next severe storm. There are a variety of ways in which the shock needed to release the avalanche can be delivered into the snowpack in the avalanche's starting zone. See Figures 1 through 18 for a depiction of each of these different active avalanche control technologies. Each involves an explosion of some kind and includes the following:

- Explosive charges delivered by hand (thrown) into the avalanche starting zone by personnel who have climbed to that position.
- Explosive charges delivered by helicopter into the avalanche starting zone.
- Explosive charges delivered by light cableways or 'bomb-trams' installed expressly for this purpose.
- Explosive charges delivered by civilian 'mortars' located in or near the avalanche starting zone and fired remotely by personnel from the highway or a similar secure position.
- Explosive charges delivered by compressed air cannons from a secure position.
- Explosive military artillery ordnance rounds fired from a secure position.
- Explosive combustion of gas mixtures in fixed facilities located in the avalanche starting zone and fired remotely by personnel from a secure position.
- Explosive combustion of gas mixtures in helicopter deployable portable facilities located in the avalanche starting zone and fired remotely by personnel from secure positions.

Source: R. Decker.

Figure 1. A typical explosive charge used to initiate avalanches while a threaten highway is temporarily closed. It can be delivered into the avalanche starting zone by personnel who have climbed to that position, by helicopter, or from a 'mortar' located in or near the avalanche starting zone.

Source: Associated Press Year (2006)

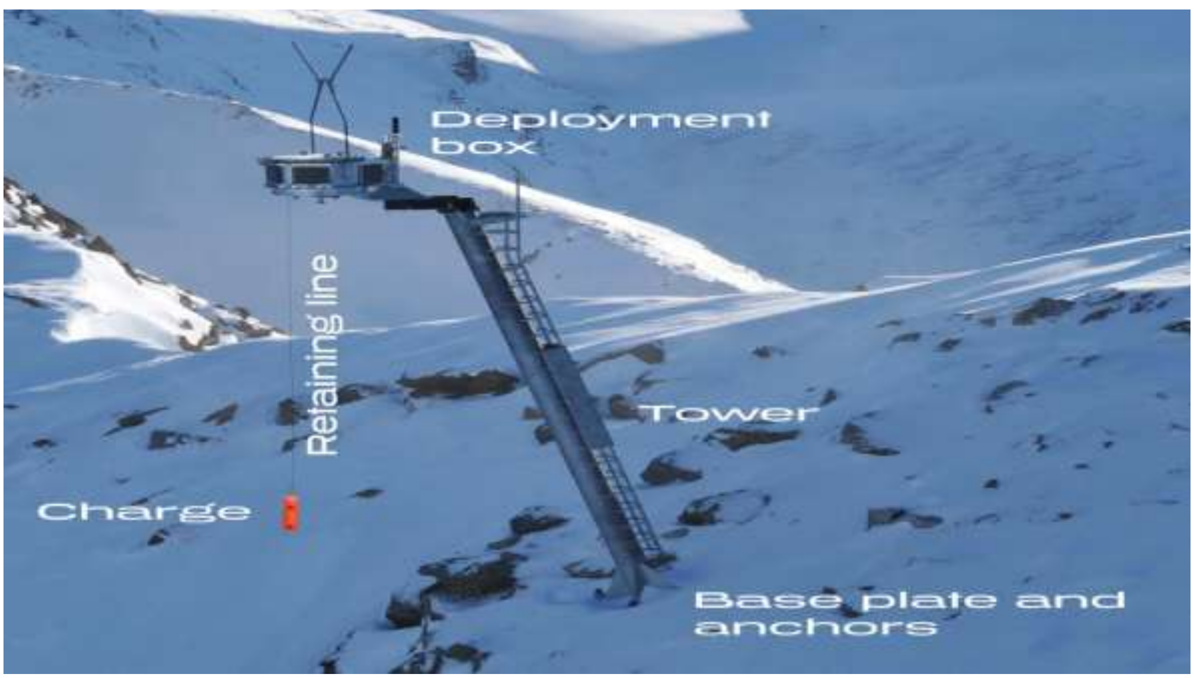
Figure 2. An explosive hand charge being thrown into an avalanche-starting zone at the Copper Mountain ski area, Colorado.

Source: Jackson Hole Magazine, March 4, 2015

Figure 3. A WYDOT avalanche control technician preparing to heli-bomb the "Cow-of-the-Woods" avalanche threatening a closed portion of US 189/191, in Hoback Canyon, Wyoming. This avalanche is now actively controlled with the TAS O'Bellx® portable gas exploder.

Source: Desplom

Figure 4. A light cableway or ‘bomb-tram’, (cable for transporting explosives, CATEX®), for delivering avalanche control explosives to the avalanche starting zone where they can be detonated remotely.



Source: Wyssen Avalanche Control AG

Figure 5. A remotely operable explosive deploying technology, by Wyssen Avalanche Control, in an avalanche-starting zone in the Alps.

Source: Wyssen Avalanche Control AG

Figure 6. The Wyssen Avalanche Control explosive delivery technology is also portable and explosives can be dropped from it while it is hanging from a sling cable below the helicopter.

Source: R. Decker.

Figure 7. A remotely operable avalanche control 'mortar', a Doppelmayr® Avalanche Guard®, near multiple avalanche starting zones above State Route 22, on Teton Pass, Wyoming.

Source: Maple Leaf Powder

Figure 8. A Doppelmayr® Avalanche Guard® in the Austrian Alps in firing mode with its door open.

Each individual explosive round from the Avalanche Guard® can target a different nearby avalanche starting zone. In Figure 8, note the deployments of passive/constructed snow supporting structures in the avalanche starting zones on the opposite side of the valley, defending the developed valley floor below.

The Avalanche Guard® has found widespread implementation in Europe, but not the United States. The single biggest deterrent to its domestic implementation is the requirement that it meet all Bureau of Alcohol, Tobacco and Firearms (BATF) explosive cache requirements. This resulted in a unit that is considerable heavier and more expensive to manufacture than its European counterpart. Nonetheless, the two aging Avalanche Guard® units that are found in domestic implementation remain reliable, to date. One of these is WYDOT's Avalanche Guard® above State Route 22, on Teton Pass.

Source: Avalanche Busters Primitive Survival

Figure 9. A compressed air launcher, Avalauncher®, being used in the Alta ski area, Utah, to deliver an explosive charge into avalanche starting zones.

Source: Denver CBS

Figure 10. An Avalauncher® being operated by Colorado DOT personnel from a vehicle mounted platform.

The Avalauncher® active control technology utilizes compressed gas to launch a subsonic explosive projectile. The projectile becomes armed shortly after leaving the barrel of the launcher by releasing the safety on the full range of motion of the firing striker pin. Upon impact, this inertial striker pin impacts and fires a percussion cap directly into a traditional fire controlled blasting cap that then ignites the explosive. It has been an effective active avalanche control explosive shock delivery system for decades. It's evolution dates from the early 1960's and the very earliest experiments in active control technology, being driven by the avalanche security needs of the winter Olympic venue under development at Squaw Valley, California [Brennan, 2006]. The Avalauncher® infrastructure is not costly. However, on a per round basis, the individually molded plastic explosive rounds exceed the same costs per round for a well supplied military weapons program. Both the Avalauncher® and the military weapon perform the same function of delivering an avalanche initiating shock accurately to avalanche starting zones from secure locations. The Avalauncher® has been utilized from both fixed and mobile (snow cat and truck) platforms. The latter being a valuable attribute for DOTs utilizing them for active avalanche control along a highway corridor with multiple avalanche starting zone targets.

On March 31, 2014 a premature detonation of an Avalauncher® explosive round during launch injured two of the three Colorado DOT operators on-site [KDVR, 2015]. As a consequence, CDOT suspended the use of their Avalaunchers® for active control, a technology they rely upon heavily in their active avalanche control program, firing on the order of thousands of Avalauncher® rounds per year. So as to bring this critical active control technology back online in a timely fashion, CDOT aggressively evaluated and implemented refreshed firing procedures and established either the safe perimeter for the blast zone of an Avalauncher® round, or implemented armored firing stations for their operators [CDOT, 2016]. These leadership efforts are being heeded by other organizations, both ski area and DOT, that rely heavily on the Avalauncher® in their active avalanche control programs.

WYDOT utilized an Avalauncher® for a short period during the verily earliest years (1972) of its avalanche control and defense program [Yount, 2016]. An Avalauncher® is not a technology utilized today in WYDOT's active avalanche control program.

Source: Jackson Hole News and Guide

Figure 11. A military artillery weapon being used for active avalanche control by WYDOT personnel from a secure position on State Route 22, on Teton Pass, Wyoming.

Source: New York Times

Figure 12. A typical explosive round of military ordnance being used for active avalanche control by Utah DOT personnel, in Little Cottonwood Canyon, Utah.

Military artillery was first used to initiate avalanches onto enemy troops on both sides of the mountainous Austrian-Italian front during World War I [Root, 2008]. Military weapons found there first domestic implementation for active avalanche control in Alta, Utah in the late 1940's [Abromeit, 2004; Atwater, 1968]. In 1972, military weapons were implemented for active avalanche control for WYDOT's nascent avalanche control and defense program, in and around Jackson, Wyoming [Yount, 2016]. Of all the available active avalanche control shock sources found in domestic highway applications, more rounds have been fired from military weapons for this purpose than any other technology.

Source: R. Decker.

Figure 13. A fixed, remotely operable avalanche initiating gas exploder, GAZEX®, in the Alps.

Note in Figure 13 the solid steel vertical inertial anchor for the GAZEX® that can rise off its foundation during firing. Because it is pin connected, the other forces being produced by the gas explosion do not produce a bending moment in the firing tube or its foundation in the left of the photo.

Source: Jackson Hole News and Guide

Figure 14. A summer test firing of a GAZEX® in the avalanche-starting zone above State Route 22, Teton Pass, Wyoming.

Source: Unofficial News

Figure 15. A Colorado DOT deployment of a multiple modern GAZEX®.

Note the gas exploder in the foreground of Figure 15 has no inertial anchor. All the loads and bending moments being created by the gas explosion are transmitted to a single foundation, which in this photo is buried in the snow at the base of the exploder tube. These loads are not carried entirely by the exploder tube, but are also taken up by flexible, GAZFLEX® laterally steel supports that run parallel to the exploder tube itself.

The GAZEX® and the more recent GAZFLEX® line of mixed gas exploders, manufactured in France by TAS, have been in service in the European Alps since 1989. Not long after this, in 1991, the first domestic GAZEX® was installed by Caltrans, in the Echo Pass summit of US Route 50, enroute between Sacramento and South Lake Tahoe. WYDOT installed their first two GAZEX® above State Route 22, on Teton Pass, the following year, in 1992 [Gorsage, B., 2018].

Some of the oldest GAZEX® installations, dating from the early 1990's, are in Cervina, Italy and in Kootenay Pass, Canada and have each been fired an estimated 1000 times [Bristow, 2018]. The consequence of 30 years of GAZEX® implementation and development is that it is now a highly evolved, effective, reliable active avalanche control shock source technology.

Source: Adventure Journal

Figure 16. WYDOT's remotely operable, portable/helicopter deployable TAS O'Bellx® gas exploder, above US Route 189/191, in Hoback Canyon, Wyoming.

In Figure 16, note the tennis ball sized grapple connection at the top that allows a helicopter to place and recover the TAS O'Bellx® from its pedestal without the need for personnel onsite.


Source: General Aviation News

Figure 17. This is WYDOT's first TAS O'Bellx® being lifted from the staging area for deployment in Hoback Canyon, Wyoming, above US Route 189/191.

The TAS O'Bellx® gas exploder can be placed on its pedestal and recovered by helicopter, without the need for personnel at the exploder site. The first TAS O'Bellx® portable/helicopter deployable gas exploder found service in the Orelle ski area, in France, in 2011. Like the GAZEX® fixed gas exploders, they are manufactured in France, by TAS. The first domestic implementation of a TAS O'Bellx® gas exploder was WYDOT's initial unit in Hoback Canyon, above US Route 189/191, installed in 2013. A second TAS O'Bellx® was installed in the adjacent avalanche path, the "Calf-of-the-Woods", in Hoback Canyon, in 2015.

It is estimated that a TAS O'Bellx® unit in La Clusaz, France, installed in 2012, has now been fired over 150 times [Bristow, 2018]. TAS O'Bellx® portable gas exploder technology has shown to be highly effective and reliable, though unlike the fixed GAZEX® exploders, the TAS O'Bellx® technology has not yet enjoyed multiple decades of firing and the development that inevitably results from both longevity in service and high firing rates.

Source: George Kourounis furiousearth

Figure 18. A modified gas exploder, the TAS Daisy Bell®, is portable and can be fired from its sling cable below a helicopter.

The fact that such a plethora of technology exists for this specific transportation safety application is indicative of the fact that no single avalanche shock source technology is optimal for all sites and none are without their drawbacks. Regardless of the specific technology being utilized, avalanche forecasting and active control is fraught with three distinct and demanding challenges:

1. It is a personnel intensive activity that to be effective must be practice by skilled individuals at the local/maintenance facility level, and in the event that active control activities are successful, cleanup of avalanche debris from the highway may be required. These most often require equipment and operators of the front end loader and/or rotary snowplow variety.
2. The avalanche hazard on an affected highway does not leap to 'high' at the very moment that DOT personnel close the highway to motorists. The hazard or propensity for avalanches is escalating, even while the highway is still open, and if active avalanche control activities are not successful in releasing the offending avalanches, this hazard may remain high, leaving DOT personnel with the quandary of whether or not to re-open the highway.
3. Active avalanche control requires highway closures and subsequent delays, and in one of its greatest ironies, if active avalanche control is successful in bringing down the avalanches, these delays are exacerbated to include the duration of the requisite cleanup, as well.

Source: ITD

Figure 19. The consequences of successful active avalanche control can exacerbate highway closures for clean-up, like that seen here on State Route 21, in Banner Summit, Idaho.

Source: WYDOT

Figure 20. A vehicle thrown from State Route 22, on Teton Pass, Wyoming, in December 2016, by an avalanche that had been released by a backcountry skier just prior to a planned active avalanche control mission.

The need to clean-up avalanche debris after active avalanche control is, nonetheless, a much improved situation over this very uncommon one depicted in Figure 20, above; a vehicle thrown from State Route 22, on Teton Pass, Wyoming, in December, 2016, by an avalanche that had been released by a backcountry skier just prior to a planned active avalanche control mission.

3.2. Passive/constructed avalanche defense

Unlike avalanche hazard forecasting and active control, passive/constructed avalanche defense technologies were pioneered in Europe [Schilcher, 2015; Swiss Federal Institute for Snow and Avalanche Research, 2007] where the density of population, travel corridors and valley floor development precluded the implementation of regular highway (and rail) corridor closures and the purposeful initiation of avalanches onto populated valley floors.

Despite the dramatic difference in their guise and implementation over active avalanche control, passive/constructed avalanche defense is as effective in managing highway avalanche hazard as active avalanche control. Passive/constructed avalanche defenses found their first domestic applications with North America's earliest railroading activities, in the mid and latter 1800's, on the Canadian Pacific railroad through the Canadian Rockies, and on the Union Pacific Railroad, in the Sierra Nevada Mountains of California. Only recently have passive/constructed avalanche defense technologies been reconsidered and implemented on United States domestic highways, including WYDOT's RM 151 Avalanche above US Route 189/191 in south Jackson [Hewes, 2010; Hewes, 2013; WYDOT, 2009].

As the name would imply, passive/constructed avalanche defense technology utilizes engineered and constructed facilities in the avalanche starting zone to preclude the onset of an avalanche in the first place, or facilities at the highway that allows naturally releasing avalanches to safely pass over the highway. These include:

- Snow supporting structures (snow bridges or rakes – the difference being horizontal or vertical stringers, respectively) in the avalanche starting zone that support the snowpack's weight in place, and preclude the onset of avalanching.
- Avalanche sheds or galleries at the highway where the highway is crossed by the offending avalanche. Avalanche sheds allow the avalanche to pass over the highway without risk or delay to motorist on the affected section.

Source: R. Decker

Figure 21. A snow supporting structure (a snow bridge, with horizontal members) being installed with a helicopter in the RM 151 Avalanche starting zone, above US Route 189/191, above the South Park area of urbanized south Jackson, Wyoming.

Source: J. Yount

Figure 22. WYDOT's RM 151 Avalanche snow supporting structures doing their job in the upper reaches of the avalanche-starting zone, above US Route 189/191, south of Jackson, Wyoming.

Source: remonte-mechanique

Figure 23. The extent of a typical deployment of snow supporting structures in the Alps.

Source: ASCE

Figure 24. Snow-net snow supporting structures.

In an alternative form, Figure 24 shows snow supporting structures where the load bearing members are flexible nets, as opposed to rigid structural members. Since the snowpack can yield or creep through these nets, unlike the rigid structures depicted in Figure 21 through 23, the foundation systems do not need to be as robust.

Source: TransBC

Figure 25. The motorist's point-of-view entering an avalanche shed in the Canadian Rockies.

Source: gregmccausland.blogspot.com

Figure 26. Inside an avalanche shed in the mountains of Chile. Note the impressive total length of avalanche shed at this site.

Source: WSL

Figure 27. An avalanche shed defending a multi-lane, divided highway in the Alps.

3.3. WYDOT's avalanche control and defense program

Starting in the mid and late 1960's, WYDOT sought to better control and defend its highways from avalanches in and around Jackson, Wyoming. The early focuses, as today, were State Route 22 in Teton Pass, and US Route 189/191 in Hoback Canyon.

In 1968, an attempt was made to span the Glory Bowl avalanche runout zone on State Route 22 in Teton Pass with a traditional steel frame bridge. At that time, the impact forces and resulting lateral loads due avalanches and their attendant air blasts were poorly understood. As a consequence, the Crater Lake Bridge was lost to an avalanche before it could be completed [Yount, 2016].

In a little known fact about WYDOT's avalanche control and defense program, passive/constructed defense was the first successful avalanche control or defense technology of any kind implemented by WYDOT. During the realignment of US Route 189/191 in Hoback Canyon, planned in 1968 and completed in 1970, avalanche barrier mounds and deflection dams were constructed for the "Bull-of-the-Woods" avalanche runout zone to slow any avalanche that might get started on its own and hopefully keep it from reaching the highway below [FHWA, 1968]. During this era of domestic highway construction, highway design and construction plans were generated by the Federal Highway Administration (FHWA). The FHWA plans for US Route 189/191 realignment and its passive/constructed avalanche defense barriers and diversion in Hoback Canyon were prepared at FHWA Region 9 Headquarter in Denver, Colorado. The "Bull-of-the-Woods" avalanche is a large, uncontrolled avalanche just east of the "Cow-of-the-woods" and "Calf-of-the-Woods" avalanches in Hoback Canyon. It can be seen in the upper left portion of Figure 34, an image of the "Cow-of-the-woods" and "Calf-of-the-Woods" avalanches in Hoback Canyon from the WYDOT Avalanche Atlas. Because of the highway realignment, it no longer threatens US Route 189/191, though it continues to avalanche regularly.

To date, there has been speculation as to who actually designed this passive/constructed avalanche defense facility. They are not identified on the "Bull-of-the-Woods Avalanche Defense" plan sheet from the realignment construction plans. The designer of this first use of constructed/passive avalanche defense in WYDOT's avalanche control and defense program remains unknown to date. Because of the use of avalanche barrier mounds and deflecting dams was an established passive/constructed avalanche defense technology in Europe during and prior to this time, most experts agree that the designer of the "Bull-of-the-Wood" facility had design experience with passive/constructed avalanche defense technology. This facility can still be seen today in the bottom of the large side-valley, on the south side of the Hoback River, east of the "Cow-of-the-Woods" avalanche on US Route 189/191.

By 1972, WYDOT maintained an operational avalanche control and defense program for the highways in and around Jackson [Yount, 2016], that included the first implementation of both military weapons and an "early generation Avalauncher® (that) was used for targets on Twin Slides" [Yount, 2016]. The Twin Slides avalanches are also on State Route 22 in Teton Pass. The use of Avalauncher® active avalanche control technology was superseded during this early era by the growing use and reliance on military weapons for active control in WYDOT's program. WYDOT never took up the Avalauncher® technology after that and does not utilize Avalauncher® active avalanche control technology today.

WYDOT has an earned reputation at trying, and being the first to try, multiple different novel avalanche control and defense technologies in an effort to improve their own program, and others, where possible. This is due in very large part to three elements:

- Numerous and highly engaged WYDOT Research Advisory Committee (RAC) project champions that arose from WYDOT's District 3 technical and operational leadership. This included multiple District Maintenance Engineers, as well as the District Engineer and Construction Engineer during the RAC supported 65% design for the snow supporting passive/constructed structural defense now found in the RM 151 Avalanche starting zone above US Route 189/191 in south Jackson.
- The 'on the ground' assistance of WYDOT avalanche program personnel in the Jackson Maintenance facility and their immediate supervisors in the Maintenance Foreman role. Project success without this cooperation would have been unattainable. Their assistance amounted to tens of hours of assistance, on multiple projects, over a period of decades.
- The logistical and administrative assistance of WYDOT's centralized Research Center in Cheyenne, and ultimately the financial support of the Research Center, again, over multiple projects and decades.

Of these efforts some were clearly successful in moving new methods and technologies into WYDOT's avalanche control and defense program, in particular the O'Bellx® portable gas exploder active control technology in Hoback Canyon and the successful passive/constructed snow supporting defense structures in south Jackson.

To be complete and accurate, there are also research and technology implementation trials that did not lead to widespread implementation in WYDOT's program in Jackson. However, and more often than not, those projects that culminated with negative results were as valuable in pointing towards alternative technologies to investigate, as they were setbacks. In some cases, the concepts investigated with WYDOT support have subsequently been taken up by others, particularly the Europeans, and developed further.

Starting in the late 1990's attempts were made to detect the inundation of the highway with debris from naturally occurring avalanches and provide highway dispatchers with an automated notification of this. The goal was neither active control OR avalanche defense, but agility in reaction time based on real time knowledge of the onset of avalanching to the highway. The scenario would be to then close the road manually or with some novel automated action. Moreover, and by design, avalanche sensors were also placed high above the highway to provide DOT maintenance workers who may be clearing debris from a previous avalanche a shrill audio alarm and a few tens of seconds to get out of the way of the next one. The initial feasibility work for this technology was supported by a NCHRP ITS-IDEA award. WYDOT was a partner in the follow-on multi-state (with Colorado, Utah, and Washington) pooled fund implementation trials, which included avalanche sensors, on-site motorist dynamic signage, and the in-vehicle claxon audio alarm for maintenance workers on the "Cow-of-the-Woods" avalanche on US Route 189/191 in Hoback Canyon [Rice, 2000; Rice, 2002; Decker, 2003]. With the exception of the motorist information signage that is now turned on and off manually, none of this trial infrastructure is still operating or in use.

Utilizing this same paradigm of the inherent value in real time detection of an offending avalanche in motion the WYDOT Research Center also support an investigation into the use of infrasonics, the very low frequency, inaudible ‘rumble’ of an avalanche for avalanche detection [Yount, 2016]. Infrasonic avalanche detection did not dig in as an operational tool in WYDOT’s avalanche control and defense program, either.

Nonetheless, the use of automated avalanche detection and alarm systems for knowledge based and real time avalanche security actions, such as highway and rail corridor closures, may have been a good idea, domestically, before its time. Using radars, infrasonics and impact switches for detection, avalanche detection and alarms were research further [Ulivieri, 2012], and have become a standard of practice in Europe, where the leadership in operational implementation is being provided by the Swiss [Meier, 2016]. During an avalanche cycle on January 22, 2018, their avalanche detection and alarm system implemented an automated closure of the short, but critical and high volume rail line into Zermatt, Switzerland based on correctly sensing a large avalanche in motion and headed for the valley floor. Zermatt is ‘car free’ and the only access to the community is via this rail line from a parking facility at Tasch, slightly down valley from Zermatt. A train departs both Tasch and Zermatt every 20 minutes. The ride duration is 12 minutes.

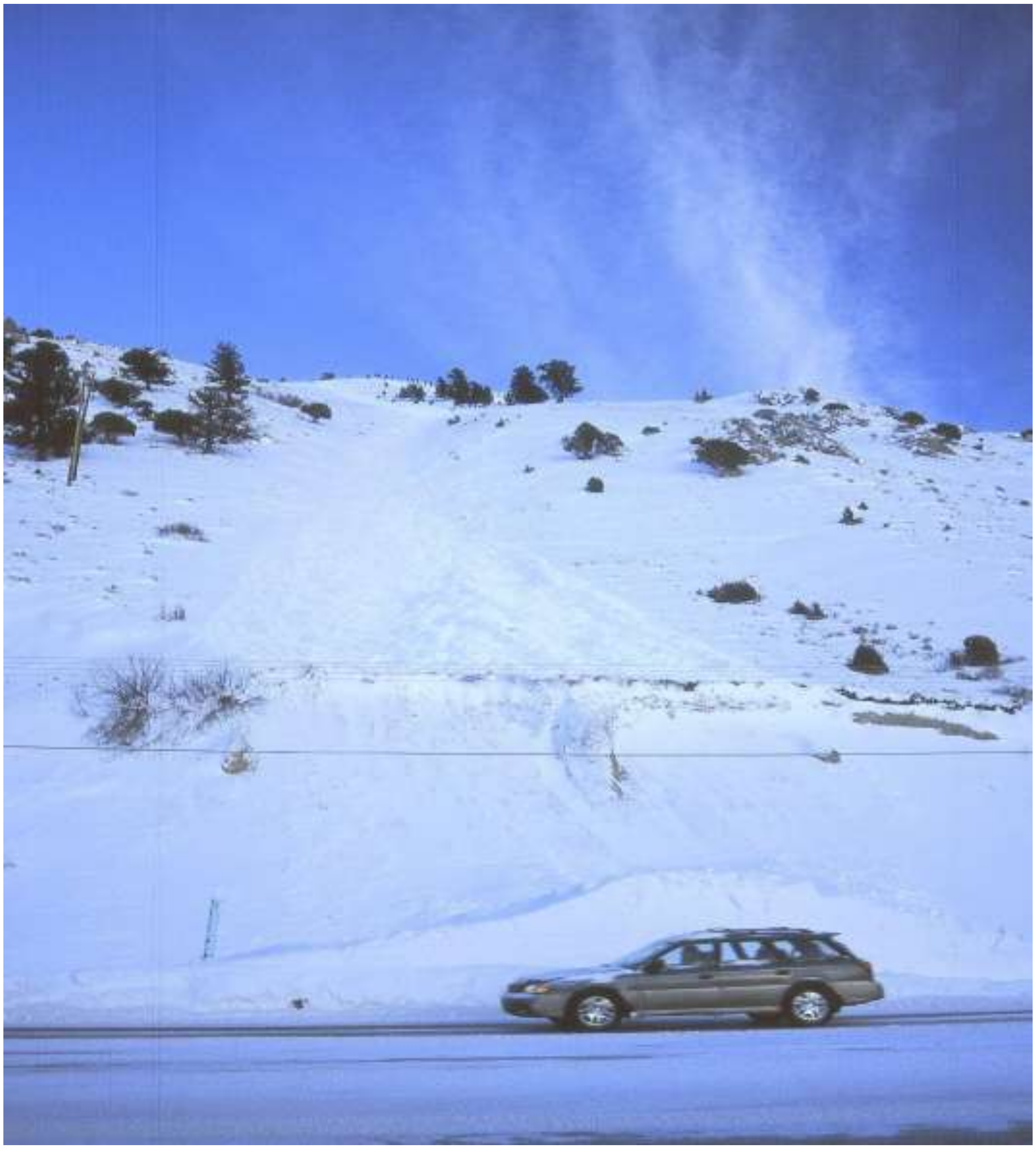
The other noteworthy WYDOT Research Center/RAC supported avalanche defense technology trial that did not lead to widespread implementation was the Snow Sail project on the RM 151 Avalanche above US Route 189/191 in south Jackson. For some time WYDOT, the residents of the South Park area of Jackson Hole, the USDA Forest Service, and US Game and Fish agreed that this avalanche was not a good candidate for active (explosive) avalanche control. An attempt was made to ‘passively’ defend US Route 189/191 from the RM 151 Avalanche with a deployment of ‘snow sails’ - low cost, light weight, hand constructed panels of fabric used to cause the wind flowing around them to roughen the avalanche slope and, theoretically, preclude avalanche fracturing and avalanching [Yount, 2004(a); Yount, 2004(b)]. One positive result of this investigation was verification that the wind and snow sails can ‘bore’ a dramatic hole in the snowpack, as seen in Figure 28. This hole in the snowpack has been completely excavated and maintained by the wind. The snow sail frame is buckling under the snowpack creep loads that have a hold of its uphill cabling.

Source: R. Decker

Figure 28. A snow sail in RM 151 Avalanche starting zone above US Route 189/191 in south Jackson.

Despite being very cost effective, the snow sails didn't work. They were superseded with the passive/constructed snow supporting structural avalanche defense now found there above US Route 189/191, in south Jackson. The snow sail deployment can be seen on the downwind side of the RM 151 Avalanche starting zone in Figure 30 from the WYDOT Avalanche Atlas. There was some speculation that they helped defend from avalanches during the smaller storms, but were ineffective during large storms, exactly the ones that US Route 189/191 needs in its defense.

On January 1, 2004, after the snow sails had been in service of three seasons, the RM 151 Avalanche came onto an open US Route 189/191 in south Jackson, as seen below in Figure 30. The decision to explore the use of passive/constructed snow supporting structures for avalanche defense in the starting zone of the RM 151 Avalanche began at this time. The feasibility and 65 percent preliminary design of the successful RM 151 snow supporting structural avalanche defense was supported by the WYDOT Research Center, its RAC, District 3 leadership, and avalanche control and defense program personnel in the Jackson.



Source: N. Reppin

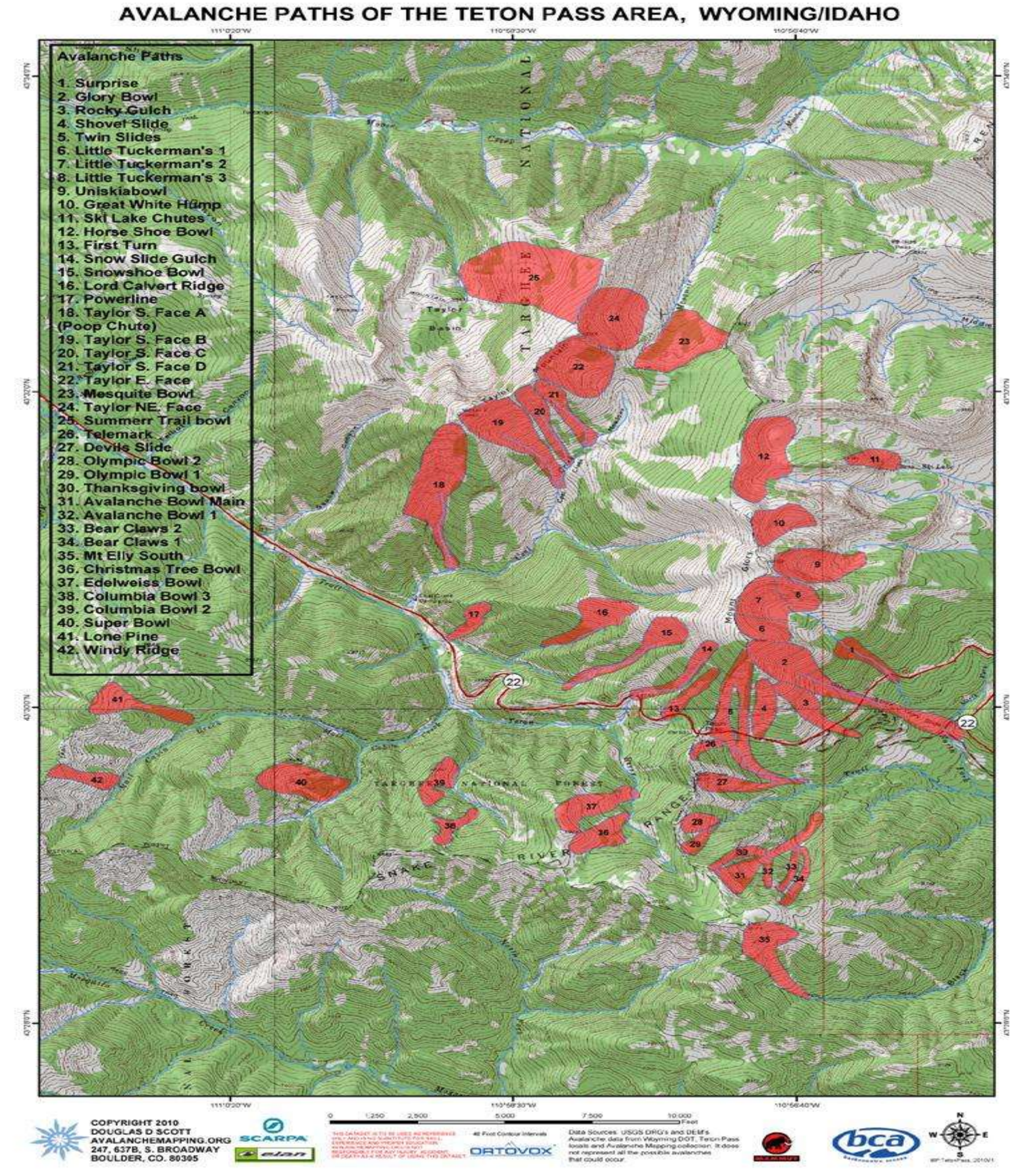
Figure 29. An avalanche from the RM 151 Avalanche onto US Route 189/191 on January 1, 2004, despite the implementation of a passive, constructed snow sail avalanche defense system.

To date, and except in extraordinary circumstances, the focus of WYDOT's modern avalanche control and defense program in and around Jackson are the avalanches that come from above State Route 22, on Teton Pass, and above US Route 189/191, in Hoback Canyon. The WYDOT avalanche control and defense program also addresses the hazard to US Route 89, in the Snake River Canyon, between the communities of Hoback Junction and Alpine, Wyoming, and to a lesser degree 'lower face' avalanches whose starting zones and run-outs are at lower elevations much closer to the valley floor. The RM 151 Avalanche on US Route 189/191, south of Jackson, only recently defended with snow supporting structures [Hewes, 2010; Hewes, 2013; WYDOT, 2009], is one example of a 'lower face' avalanche.

Of the eight active control and two passive/constructed avalanche defense technologies available for highway avalanche control and defense, WYDOT maintains or operates the following technologies on the routes set out in Table 1. The ADT count for the winter months of November, 2015 through March, 2016, for each of these routes, is also provided in Table 1 for reference, and as they becomes a factor for considering the impacts of traffic delay due to active avalanche control. Annually, summer traffic volumes are about double those of the winter months.

Table 1. Highway route, avalanche control and defense technology, and averaged daily traffic for the mid-winter months (November through March) for the winter of 2015/16, on State Route 22, on Teton Pass, and 2016/2017, on all other highways in WYDOT's avalanche control and defense program [ITD, 2016; WYDOT, 2017].

Route	Avalanche Control or Defense Technology	Average Daily Traffic 2015/16 (ITD) or 2016/17 (WYDOT)
State Route 22, Teton Pass	4 GAZEX®, 1 Avalanche Guard®, Military Howitzer	4,430 vehicles/day, ITD Station #102
US Route 189/191, Hoback Canyon	2 TAS O'Bellx®, Howitzer, Heli-bombing	916 vehicles/day, WYDOT Station #73
US Route 89, Snake River Canyon	Heli-bombing, Military Howitzer	3,110 vehicles/day, WYDOT Station #74
US Route 189/191, RM 151, Jackson	Passive Snow Supporting Structures	7,014 vehicles/day, WYDOT Station #32



Source: avalanchemapping.org

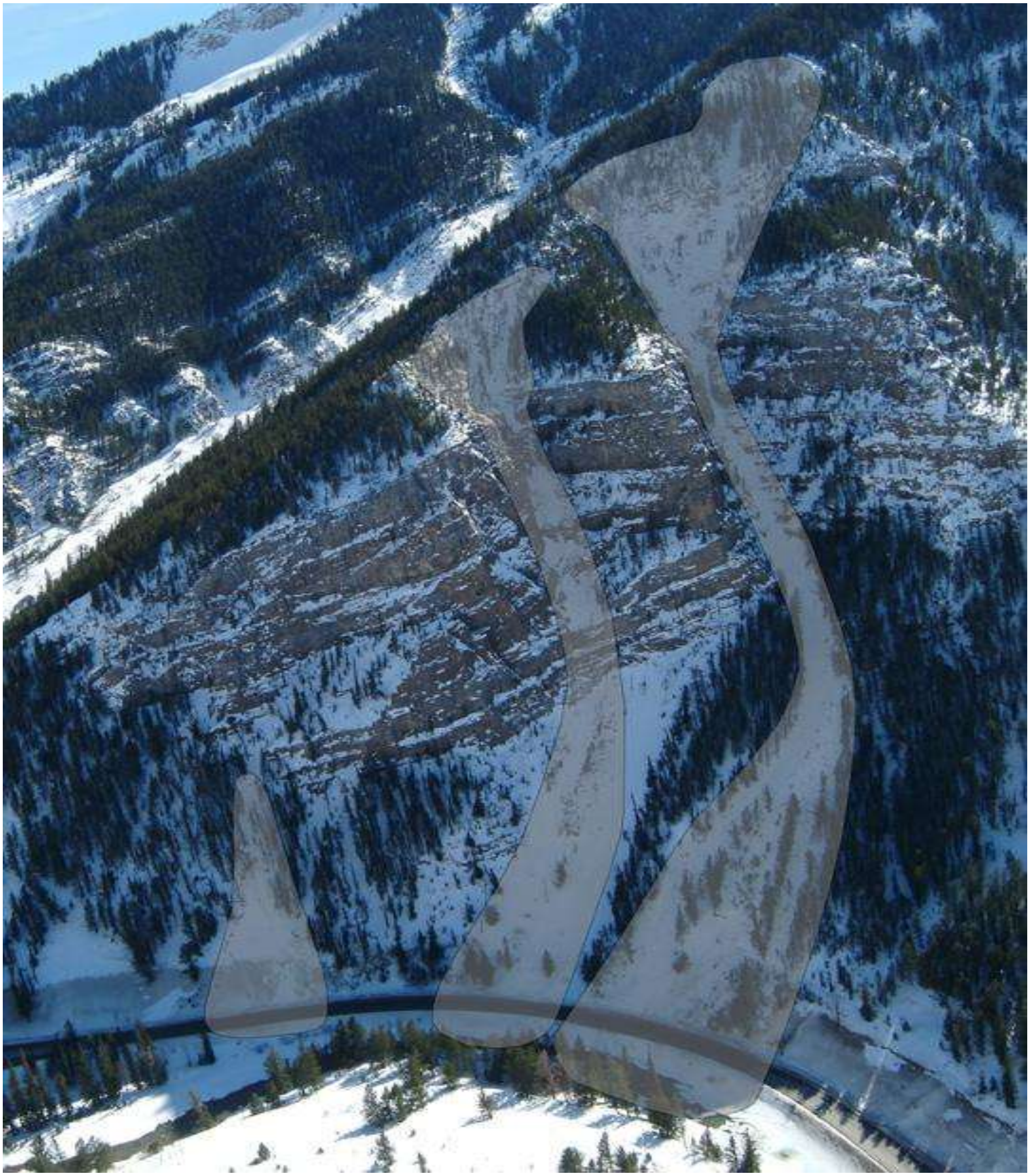
Figure 30. An avalanche map of the Teton Pass, Wyoming area showing the multiple avalanche paths in the area and those that attack State Route 22 on both sides of the Pass.

Source: Unofficial Network

Figure 31. The Glory Bowl Avalanche, one of several, and the largest on State Route 22, on Teton Pass, Wyoming.

Source: WYDOT

Figure 32. Clearing debris from the Glory Bowl avalanche on State Route 22, on Teton Pass, Wyoming, after successful active avalanche control.



Source: WYDOT altered.

Figure 33. The "Cow-of-the-Woods" and "Calf-of-the-Woods" avalanches zones, US Route 189/191, in Hoback Canyon, Wyoming.

Source: WYDOT altered

Figure 34. The RM 151 Avalanche above US Route 189/191, south of Jackson, Wyoming.

CHAPTER 4. INVESTIGATIVE METHODOLOGY AND RESULTS

4.1. Avalanche Control and Defense Cost Metrics

In the face of the numerous choices for highway avalanche control and defense, identifying the best technology for a specific site has and can be a daunting challenge, fraught with the potential for both risky and costly errors. Making these decisions has only become more challenging with the availability of modern, reliable, helicopter portable, remotely fired avalanche starting zone explosive shock source technologies.

This research examined a suite of cost metrics that may allow WYDOT and other state DOT transportation facility planners to make these avalanche control and defense technology procurement decisions in a more structured fashion.

To test the practical value of this research, its capabilities are utilized to develop recommendations for avalanche control and defense technologies for all four of WYDOT's avalanche control and defense program sites:

- "Cow-of the Woods" and "Calf-of-the-Woods" avalanche paths on US Route 189/191, in Hoback Canyon.
- Teton Pass on State Route 22.
- Snake River Canyon avalanches on US Route 89.
- RM 151 Avalanche starting zone on US Route 189/191, south of Jackson.

Traditionally, a common form of decision support for transportation planning is a cost/benefit analysis. That much is easy enough to say. The challenge in this specific instance, avalanche control and defense on highway corridors, is the complex nature of developing metrics of cost for each of the several avalanche control and defense technologies available, and then being able to compare them to each other on an 'apples to apples' basis.

The raw data used for this purpose include the following, collected and analyzed for nine winter seasons between 2008/2009 and 2016/2017.

- Active avalanche control mission summaries prepared by WYDOT's avalanche program personnel.
- Annual cost summaries for avalanche control activities in Jackson from WYDOT Headquarters' databases.
- Procurement, installation and rehabilitation costs for the various avalanche control and defense technologies found in implementation in WYDOT's avalanche control and defense program.

Metrics of cost for the avalanche control and defense technologies presently implemented by WYDOT range from obvious and simple, to relatively obscure, and include the following:

- The costs of avalanche control and defense technology procurement, installation and rehabilitation.
- Personnel costs associated with the operation of the each technology.

- Avalanche control and defense technology operating and maintenance costs.
- The impacts of travel delays resulting from active avalanche control.

4.2. Visualization and discussion of seasonal costs for avalanche control and defense technologies

The raw data, in electronic form, for WYDOT's avalanche control and defense program for the nine winter seasons evaluated can be found via the link in the Appendix of this report. That data includes hyperlinks to the individual active avalanche control mission reports prepared by WYDOT's avalanche control personnel, the cost data from WYDOT Headquarters, and the WYDOT portion of the Hamre, et al database [Hamre, 2016].

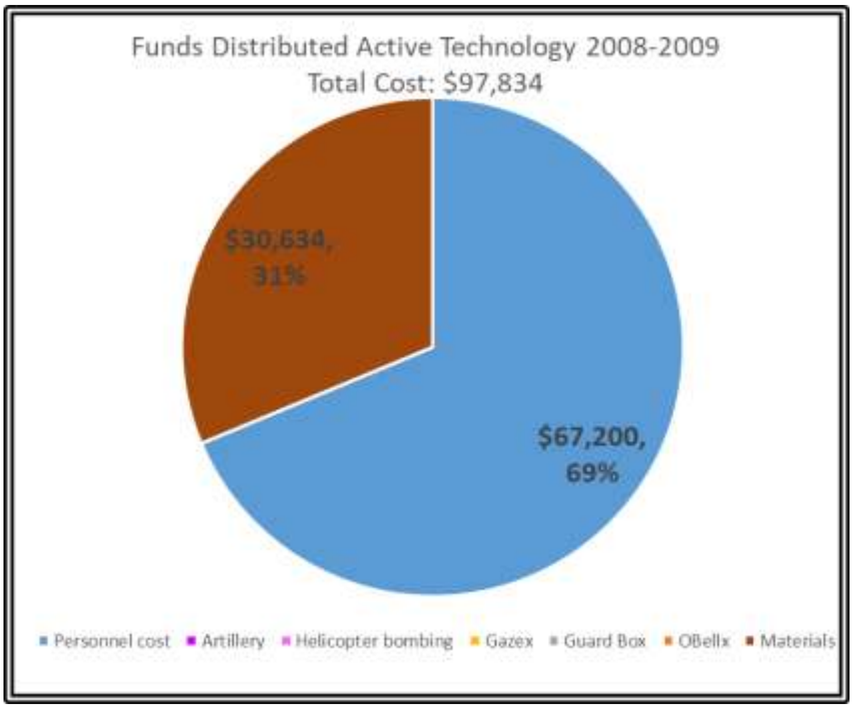


Figure 35. Funds distributed for active technology during the 2008/2009 season.

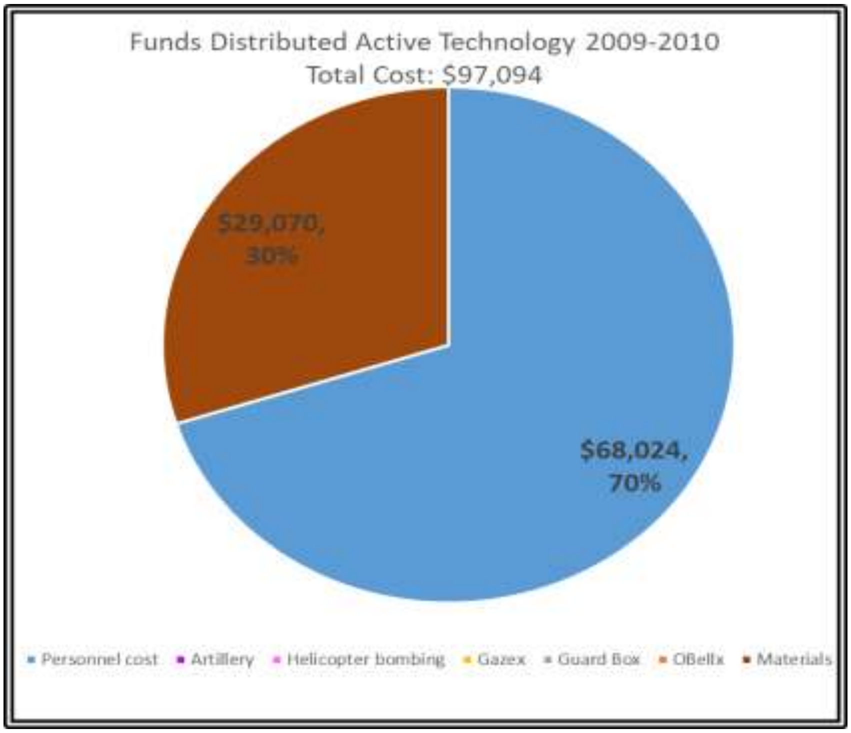


Figure 36. Funds distributed for active technology for the 2009/2010 season.

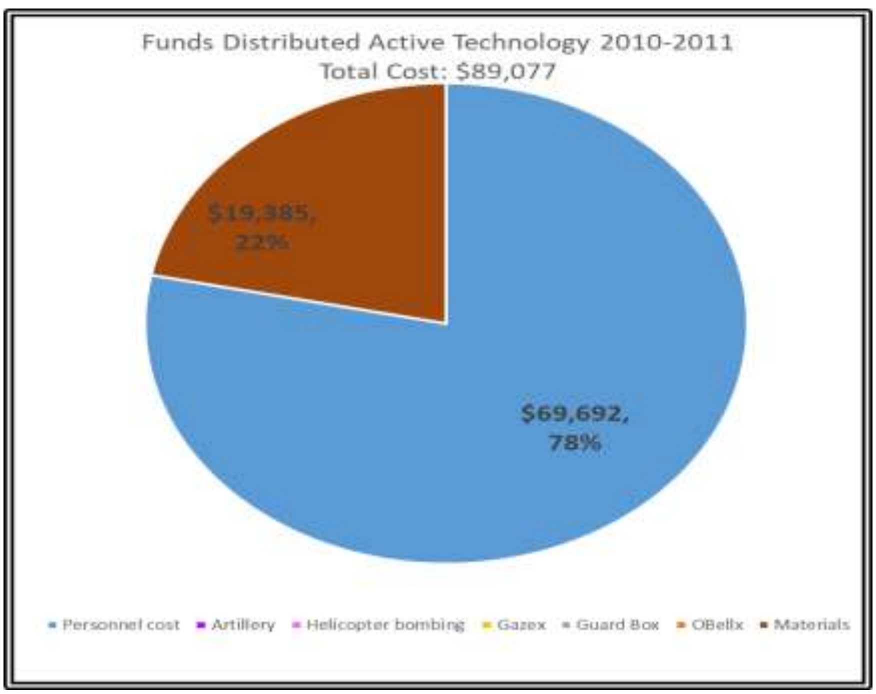


Figure 37. Funds distributed for active technology for the 2010/2011 season.

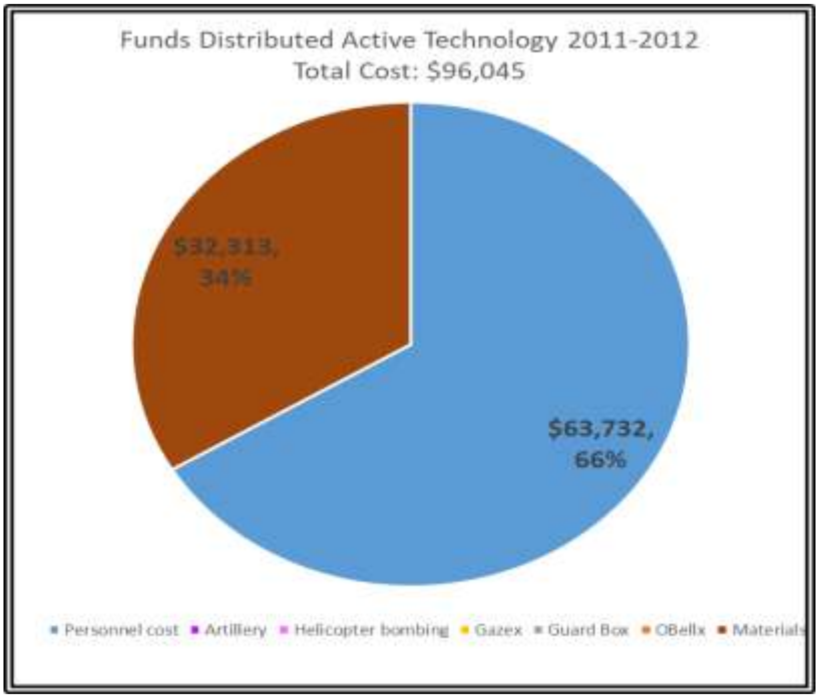


Figure 38. Funds distributed for active technology for the 2011/2012 season.

Note in Figures 35 through 38, above, that the total cost of active avalanche control activities, including personnel, for the four winter seasons of 2008/2009 through 2011/2012, range from $89,000 to $98,000 annually. As a percentage of these costs, materials and supplies for active avalanche control activities ranges from 22 percent to 34 percent of the total costs, with personnel costs making up the remainder.

During these winters, active avalanche control was the only avalanche control and defense technology in use. The portable TAS O'Bellx® mixed gas exploders, on US Route 189/191, in Hoback Canyon, and the passive/constructed snow supporting structures, on the RM 151 Avalanche starting zone, on US Route 189/191, south of Jackson, Wyoming, had not yet been implemented. Through the 2011/2012 winter season, avalanche control cost data available through WYDOT's Headquarters was not differentiated by technology.

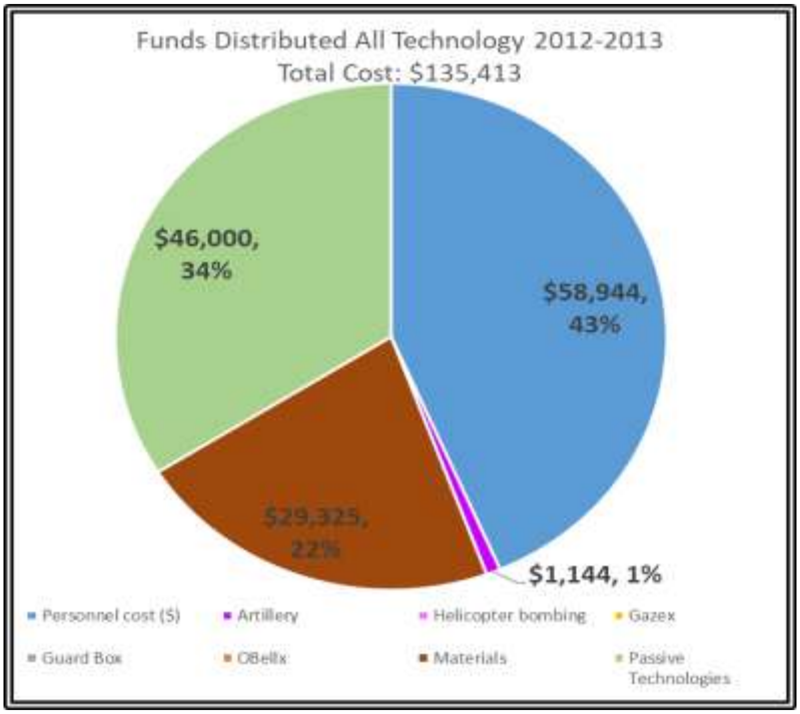


Figure 39. Funds distributed for all technologies for the 2012/2013 season.

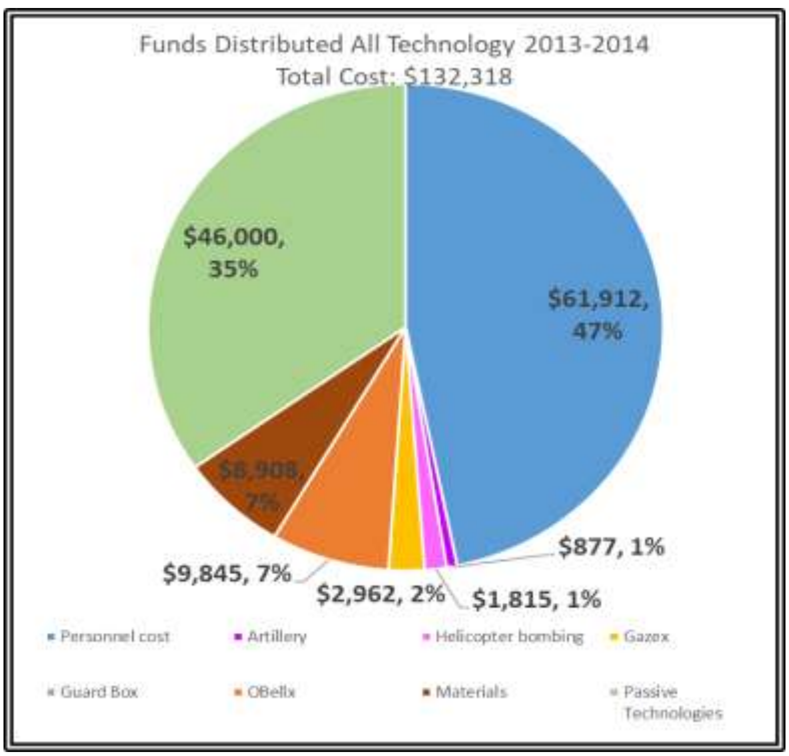


Figure 40. Funds distributed for all technologies for the 2013/2014 season.

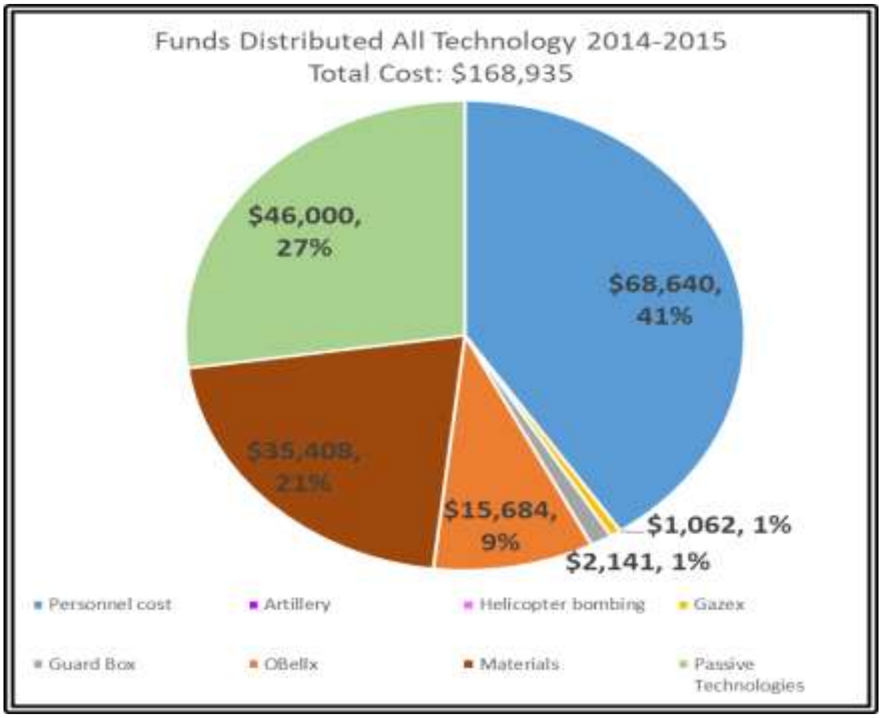


Figure 41. Funds distributed for all technologies for the 2014/2015 season.

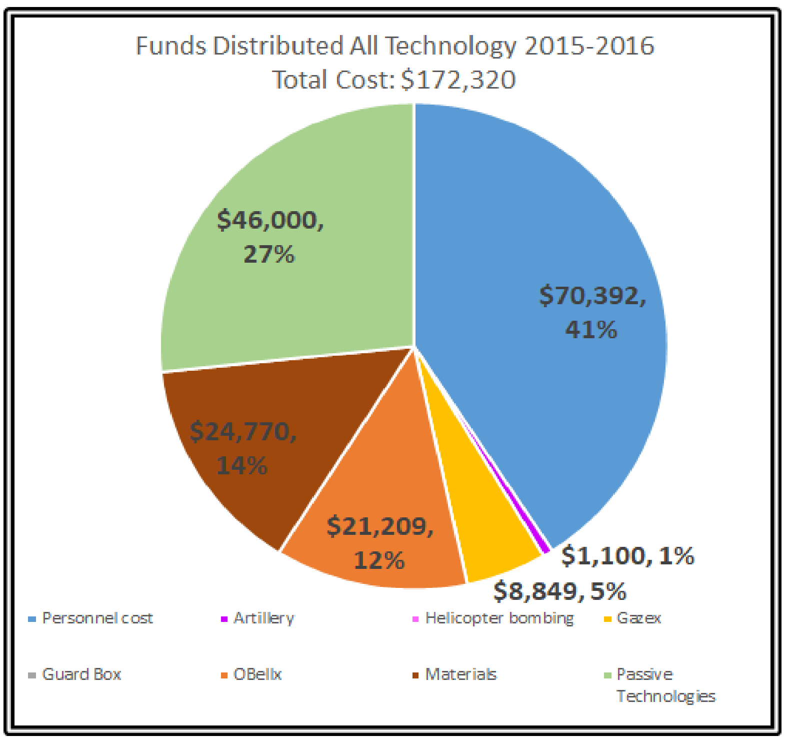


Figure 42. Funds distributed for all technology for the 2015/2016 season.

For the five remaining winter seasons of this investigation, starting in 2012/2013, WYDOT avalanche control and defense costs now include the amortized capitalization costs for passive/constructed snow supporting structural defense, on the RM 151 Avalanche starting zone, on US Route 189/191, south of Jackson, Wyoming. These seasonal costs are depicted in Figures 39 through 42.

The life span before major rehabilitation and the amortization period for the RM 151 Avalanche starting zone passive/constructed avalanche defense structures is estimated at 60 years, based on the European experience with this technology [Margreth, 2016]. As a consequence of the implementation of this passive/constructed avalanche defense, WYDOT's avalanche control and defense costs increased from an average of $97,000, in the four seasons prior 2012/2013, to an average of $135,000, for the 2012/2013 and 2013/2014 seasons.

The cost of implementing passive/constructed defense on US Route 189/191, on the RM 151 Avalanche starting zone, dominates the annual cost for all avalanche control and defense technologies at a steady $46,000 per season. This cost will be with the program another five decades. This one deployment of passive/constructed avalanche defense, as a percentage of all costs for WYDOT's avalanche control and defense program, ranges between 27 percent to 35 percent, for the winters of 2012/2013 through 2016/2017.

WYDOT's two TAS O'Bellx® portable gas exploders were implemented on US Route 189/191, in Hoback Canyon, in 2013/2014 and 2015/2016. The GAZEX® fixed gas exploders on State Route 22, on Teton Pass, were rehabilitated in 2015/2016, as well. As a consequence, WYDOT's avalanche control and defense costs grew to $170,000, in 2014/2015, and to $172,300, by 2015/0016.

Starting in the 2012/2013 season, the WYDOT Headquarters cost data now allows the material and supply costs to be differentiated by technology. Note that the net material and supply costs did not change dramatically compared to prior seasons, but the fidelity within this category of costs is much refined.

During this same period, the net cost of personnel declines modestly. Conversely, the percentage of overall avalanche control and defense costs ascribed to personnel declines from between 66 and 78 percent in the years prior to the 2012/2013 season, to 43 percent of the total costs by the 2012/2013 season.

By the 2014/2015 and 2015/2016 seasons, personnel costs for WYDOT's avalanche control and defense efforts see modest growth, back to pre-2012/2013 levels, though the net percentage of personnel costs has declined even further to 41 percent of the total seasonal costs.

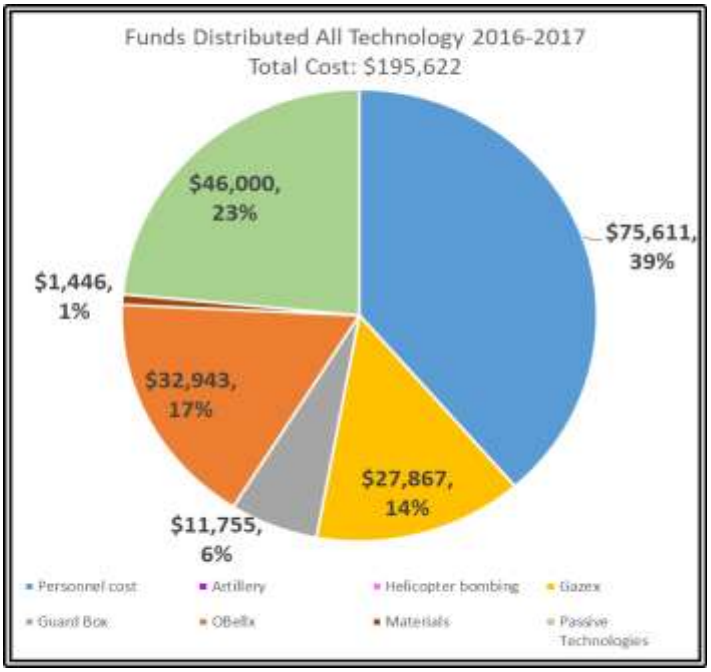


Figure 43. The cost distribution for all avalanche control and defense technologies, and personnel costs for the 2016/2017 season of avalanche control and defense conducted by WYDOT, in and around Jackson, Wyoming.

The 2016/2017 season was extraordinary for a number of reasons. NOAA's Snotel Snow Water Equivalent (SWE) now-casting system reported a basin wide SWE of 150 percent to 175 percent of normal in the watersheds in and around Jackson, Wyoming. Several of the NOAA SWE gauging stations nearest to Jackson, Wyoming, reported in excess of 200 percent of normal SWE for the period ending February 27, 2017 [NOAA, 2018].

If the best routine or ride in judged events like gymnastics or bull riding 'sets the bar' for all others, then the winter of 2016/2017, in and around Jackson, Wyoming, would have been close to a perfect '10'. It was a big winter with complicated weather patterns that included uncommonly high wind, abundant snow, warm temperatures and rain. The total number of active avalanche control missions by WYDOT avalanche personnel, during the winter of 2016/2017, was a remarkable 33 for the entire season. The outcome of these was uncommonly large natural and actively control avalanches from known avalanche paths, avalanches from paths that rarely run, and avalanches from places that no one had ever seen avalanche before.

The winter of 2016/2017 fully filled the design snowpack depth used to size the snow supporting structures used for passive/constructed avalanche defense on the RM 151 Avalanche starting zone, above US Route 189/191, south of Jackson, Wyoming. It is noteworthy that the RM 151 Avalanche starting zone did NOT avalanche during this, the severe winter of 2016/2017, when many of the 'lower face' avalanches in the area did.

The winter of 2016/2017 had a clear impact on most every cost sector of this investigation, including the total number of avalanche shots or explosions used for active control, personnel costs, and traffic delay on State Route 22, on Teton Pass, US Route 189/191, in Hoback Canyon, and US Route 89, in the Snake River Canyon.

The distribution of costs for this ‘design’ winter on WYDOT’s avalanche control and defense program can be seen in Figure 43. Total costs for 2016/2017 rose to $195,000, which is $20,000 to $30,000 greater than any previous season. Personnel costs reach their highest level in nine years, at $75,600, but fall to 39 percent of the 20161/2017 season’s total avalanche control and defense costs.

If someone were curious as to ‘how bad can it get’, the winter of 2016/2017 is a good example to use for planning purposes, including details as narrow as ‘design snowpack depth’, maximum wind speeds, extent and duration of natural and actively controlled avalanching, and traffic delay.

Figure 44. Total shots per season by technology.

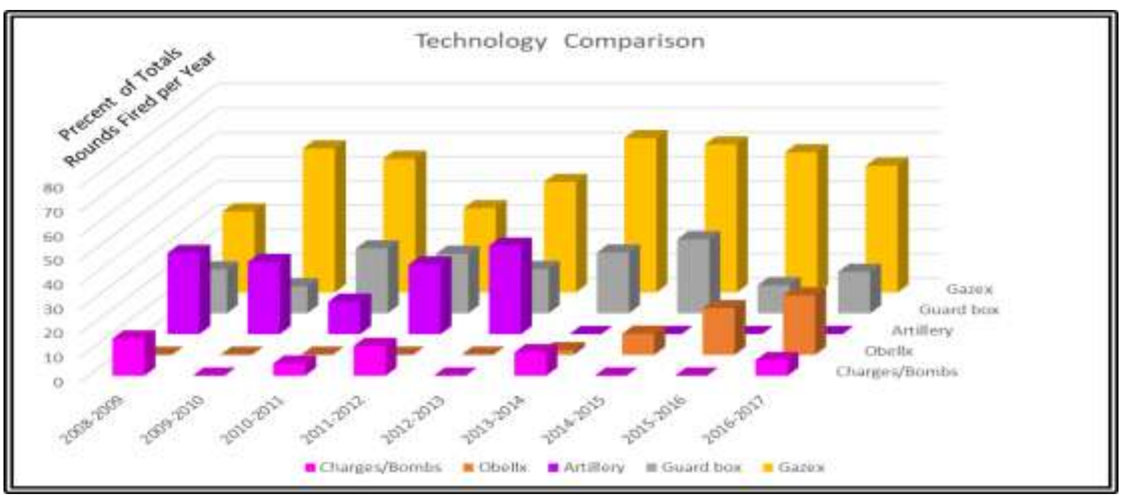


Figure 45. Total shots or rounds fired as a percentage of all shots fired by technology.

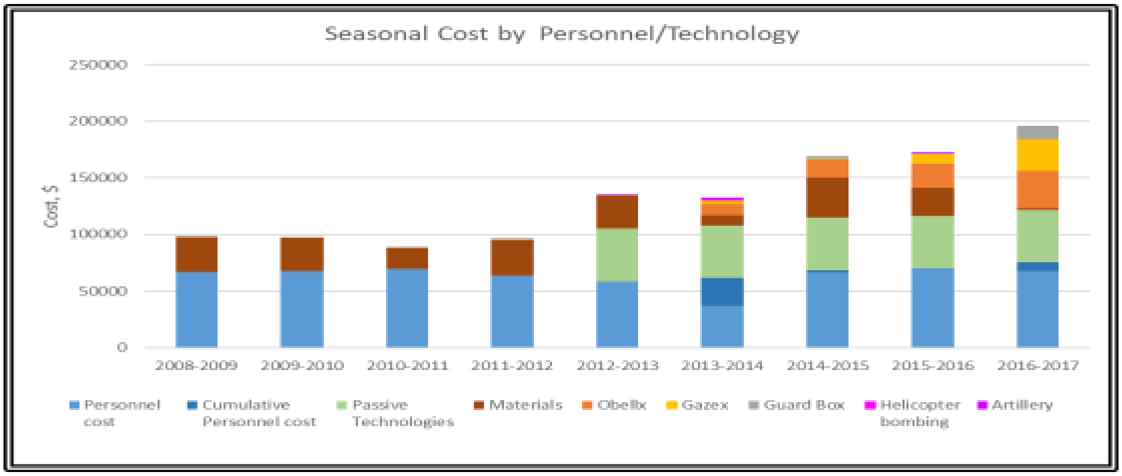


Figure 46. Seasonal cost by personnel and technology.

Figures, 44, 45, and 46 set out a summary of annual costs by technology, total shots per season by technology, and total shots or rounds fired as a percentage of all shots fired by technology for WYDOT's avalanche control and defense program in and around Jackson, Wyoming for the nine (9) winter seasons 2008/2009 through 2016/2017. In 2013/2014 and 2015/2016, TAS O'Bellx® portable gas exploders are implemented on US Route 189/191, in Hoback Canyon. The GAZEX® fixed gas exploders were rehabilitated, in Teton Pass, on State Route 22, in 2015/2016, as well.

One element of this analysis that is noteworthy is the decline in military weapon use after the TAS O'Bellx® portable gas exploders had been implemented on US Route 189/191, in Hoback Canyon, in 2013/2014 and 2015/2016. Also concurrent with this, starting in 2012/2013, the use of GAZEX® fixed gas exploders, found only on State Route 22, on Teton Pass, increased sharply. This was an additional factor in the decline in military weapon use for active avalanche control over this period.

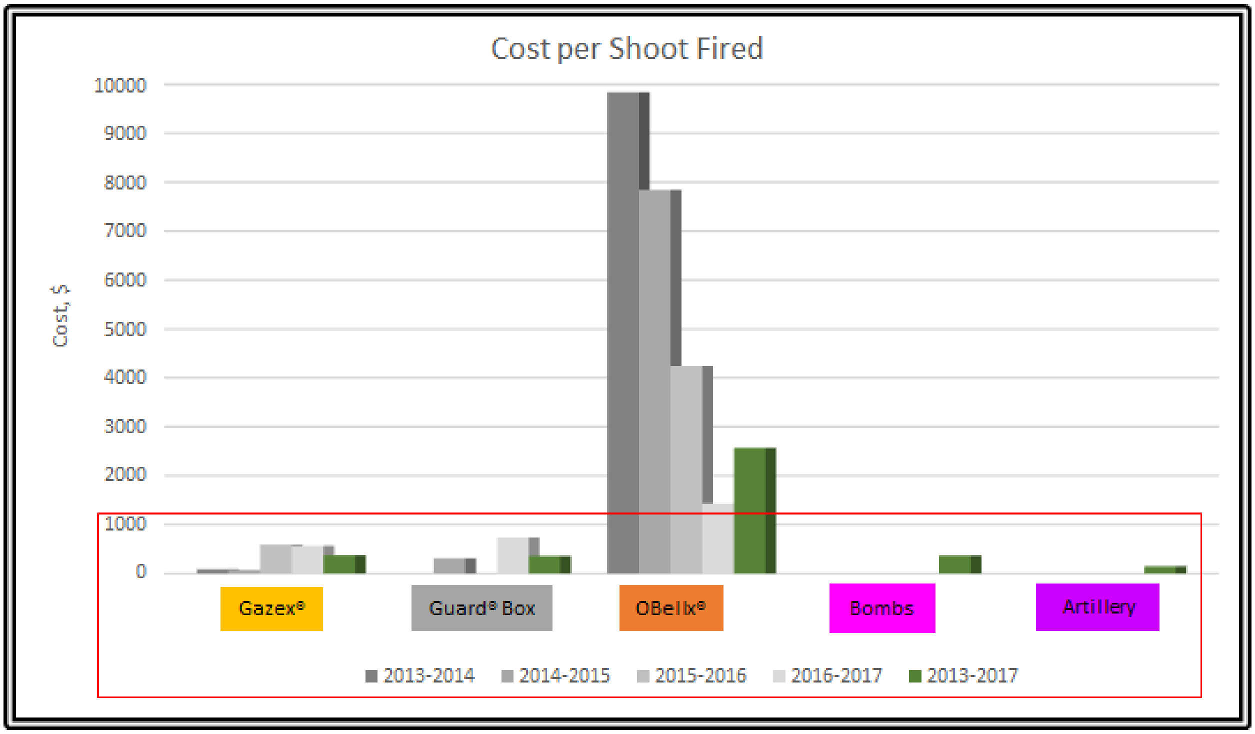


Figure 47. Costs per shot fired.

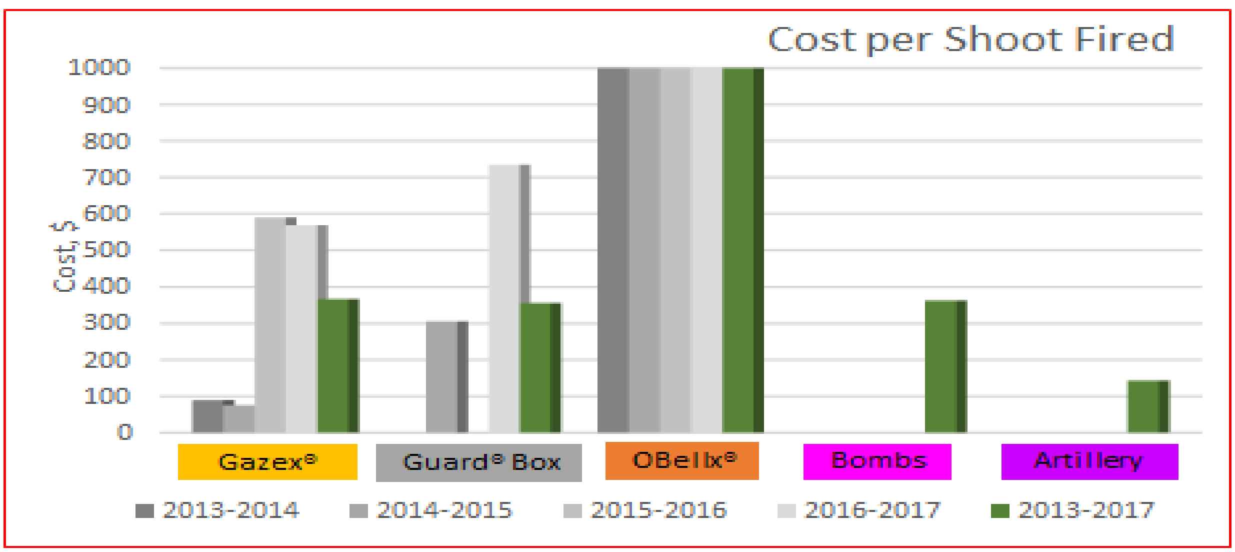


Figure 48. Cost per shot.

Figure 47 and 48 show the costs per shot fired for all technologies in WYDOT's avalanche control and defense program, starting with the winter of 2013/2014, the first season that the costs for each of the various different active avalanche control technologies became available. These Figures provide a comparison of the 'cost per shot' for each of WYDOT's active avalanche control technologies. This cost metric includes all costs associated with a given active avalanche control technology, including a fraction of the personnel costs based on the percentage of shots from that technology to total shots from all technologies, and each specific technology's costs of capitalization or rehabilitation, materials and supplies, and/or helicopter support.

Upon examination, an initial reaction may be that the TAS O'Bellx® portable gas exploder is exceedingly expensive on a cost per shot basis. This is not true. The TAS O'Bellx®' high cost per shot in this comparison is indicative of the very few total TAS O'Bellx® gas exploder shots fired since its initial installation in 2013/14 and the installation of the second TAS O'Bellx® gas exploder in 2015/2016, both on US Route 189/191, in Hoback Canyon. Note that by the 2016/17 season, as the total number of TAS O'Bellx® shots have increased, that the TAS O'Bellx® gas exploder cost per shot is approaching that of the other active avalanche control technologies.

Figure 47 shows the costs per shot fired for all technologies in WYDOT's avalanche control and defense program below the red lined threshold, starting with the winter of 2013/14, the first season that the costs for each of the various different active avalanche control technologies became available. In Figure 47, the 'green' bars are the multi-year average cost per shot by technology since 2013/14. There is a noteworthy *similarity* in the cost per shot for the GAZEX®, Avalanche Guard® Box, and hand and heli bombing. Artillery is the least expensive active avalanche control technology on a cost per shot basis.

The military weapon remains the least expensive cost per shot avalanche control technology, reflecting the fact that the weapons are 'loaned' to the various ski area and DOT programs using them for active avalanche control, including WYDOT, and the artificially low cost of explosive military ordnance rounds. The explosive military ordnance ammunition is supplied at little to no cost to the various domestic avalanche control programs that use them. Any military weapon infrastructure or procurement costs have long been completely amortized.

In contrast, the GAZEX®, TAS O'Bellx® and Avalanche Guard® Box all have annual material and (re)supply costs, including helicopter costs to perform. Those costs result in the difference in cost per shot between these other active avalanche control technologies and the military weapon.

4.3. Modern Active Avalanche Control Technologies, Reduction in Traffic Delay, Long and Short Delays

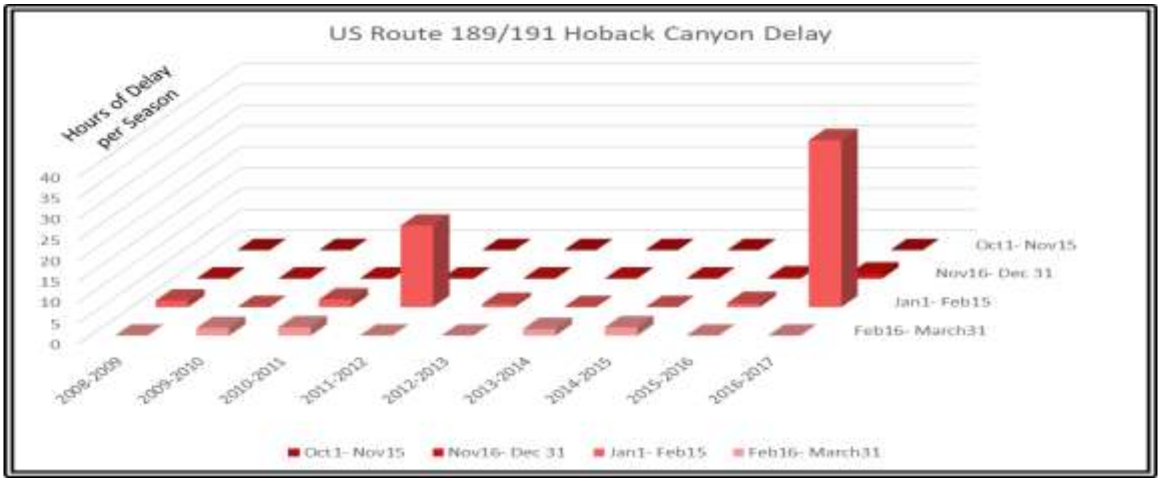


Figure 49. Seasonal traffic delay due to active avalanche control and cleanup on US Route 189/191.

Figure 49 shows the seasonal traffic delay due to active avalanche control and cleanup on US Route 189/191, in Hoback Canyon, Wyoming. In 2015/2016, the average daily traffic for the winter months of November through March was 916 vehicles [WYDOT, 2016].

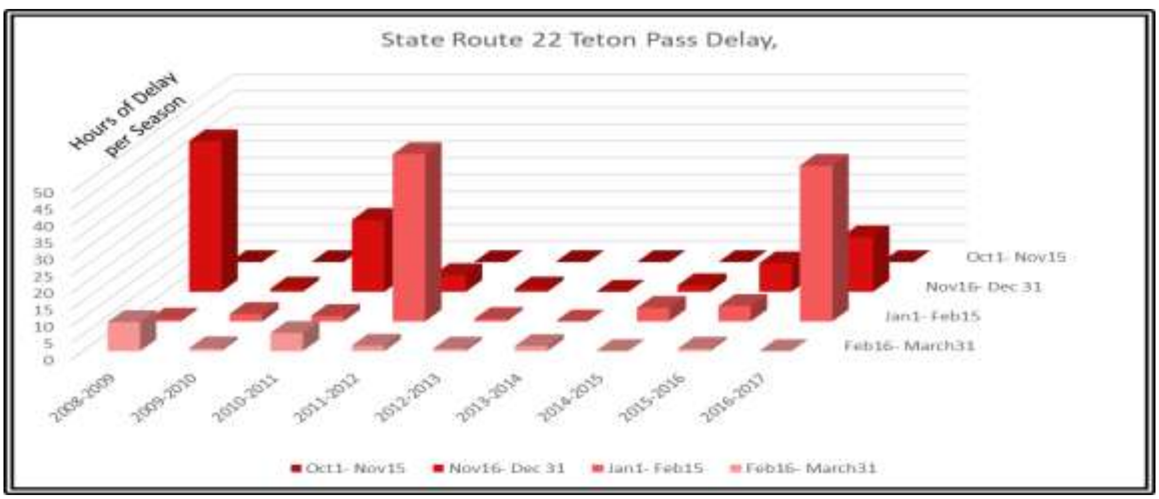


Figure 50. Seasonal traffic delay due to active avalanche control and cleanup on State Route 22.

The seasonal traffic delay due to active avalanche control and cleanup on State Route 22, on Teton Pass, Wyoming is found in Figure 50. The 2015/2016 average daily traffic for the winter months of November through March was 4430 vehicles [WYDOT, 2016].

Figures 49 and 50 show that, with the exception of the extraordinary winter of 2016/2017, and subject to variability of each winter season's severity, traffic delay due to WYDOT's active avalanche control program has been in decline since modern TAS O'Bellx® portable gas exploders were implemented on US Route 189/191, in Hoback Canyon, and fixed GAZEX® gas exploders were rehabilitated on State Route 22, on Teton Pass. This same trend was noted by WYDOT avalanche personnel, as the modernization and rehabilitation of active avalanche control technology reduced travel delays for active avalanche control missions by 60 percent [Yount, 2016].

It is important to note that some of this reduction in traffic delay for active avalanche control can also be attributed to improved mission procedures implemented by WYDOT's avalanche control personnel. All available remote fire control capabilities for active avalanche control are now brought to the site. For State Route 22, on Teton Pass, this includes having remote fire control 'in the truck' for both the fixed GAZEX® gas exploders and the Avalanche Guard® mortar. In Hoback Canyon, on US Route 189/191, this is the remote fire control for the TAS O'Bellx® portable gas exploders. In all instances now, avalanche debris clean-up equipment is brought on site *before* avalanche control firing is initiated. These modern procedures are possible, in large part, due to implementation of the modern fixed and portable, remotely fired gas exploders and mortars.

Traffic delay due to active avalanche control is inevitable. It is not just the avalanching, though. Traffic delay due to active control is the sum of both the initiation (and hence control) of avalanches and their subsequent clean-up. Further reduction in traffic delay would result from additional investment in mechanized avalanche debris clean-up capacity as well as active control technology.

Figures 49 and 50 also shows that most delays are of short duration, now estimated at an average of 52 minutes for an active avalanche control mission on State Route 22, on Teton Pass, and 26 minutes for US Route 189/191, in Hoback Canyon [Yount, 2016]. In uncommon and extreme weather conditions, the traffic delay can range from several hours to ten plus hours in duration. For the short duration delays, traffic can and will queue at the closure gates on the respective routes, and probably should not be discouraged from doing so. Conversely, long duration delays beg an alternative traffic delay strategy that should include additional motorist information and alternative queuing at locations that provide some roadside services. This strategy does not reduce traffic delay durations, but provides for some relief from its impacts.

4.4. The intangibles in avalanche control and defense

In addition to costs per shot and traffic delay measures, there are other intangibles associated with the various avalanche control and defense technologies available for WYDOT's avalanche control and defense program.

Table 2. A comparison of the intangibles characteristics of each avalanche control and defense technology available to WYDOT's avalanche control and defense program.

Technology	**Capital Cost**	**Mission Personnel**	**Personnel risk**	**Mission Duration**	**Foul Weather**	**Remote Fire**	**Fixed or Portable**	**Helicopter Deployable**
Hand Bombing	Very Low	Minimum two	High	Long duration	Up to a point	No	Portable	No
Heli Bombing	Low to moderate	Two, plus pilot	Moderate	Long duration	No	No	Portable	Yes
Military weapons	Low	Four	Moderate	Moderate to Long	Blind firing	No	Fixed or Towable	No
Avalanche Guard	Moderate	One	Moderate	Short duration	Yes	Yes	Fixed	No
GAZEX®	Moderate	One	Low	Very short	Yes	Yes	Fixed	No
TAS O'Bellx®	Moderate	One	Low	Very short	Yes	Yes	Portable	Yes
Passive/ Constructed Snow Support	High to very high	None	Very low	None	Yes	N/A	Fixed	N/A

As Table 2 shows, there is no single 'perfect' technology available to WYDOT's avalanche control and defense program.

Military weapons, despite a low cost per shot, takes a personnel team of four and can take a long time to put into position for an active avalanche control mission, if it is not already at a fixed firing location. Military weapons, by definition, are inherently hazardous.

Heli-bombing is limited to fair weather, when the propensity of avalanching may be in decline over what it was during the height of the storm. Traffic delay is exacerbated while waiting for the weather to clear.

The Avalanche Guard® explosive charge 'mortar' is caught in the morass of BATF explosive cache regulations, and has failed to take hold as a viable domestic active avalanche control technology, though it is found in widespread implementation in Europe. There is an inherent risk to personnel during the assembly and loading of the black powder mortar propellants used by the Avalanche Guard®.

The fix GAZEX® and portable TAS O'Bellx® gas exploders provide most, if not all, of the requisite intangible characteristics for safe, timely and effective active avalanche control technology. Their capital costs to procure, install and resupply are modest when compared to passive/constructed avalanche defense, but relatively high when compared to the military weapon. Like most modern active avalanche control technologies available, WYDOT's implementation of GAZEX® and TAS O'Bellx® gas exploders resulted in reduced traffic delay for active avalanche control missions.

Passive/constructed avalanche defense technologies pose little risk to personnel and requires very little personnel resources once they are constructed. They can be visually intrusive and are much more costly to implement than active avalanche control technologies. Avalanches sheds allow for avalanches to pass over them, but in almost all circumstances, the avalanche continues onto adjacent land outside of the highway right-of-way. Passive/constructed avalanche defense does not lead to traffic delays or cleanup to do their jobs.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS FOR IMPLEMENTATION

5.1. Being committed to active avalanche control

Defending highways from avalanches with passive/constructed defense is *prohibitively costly* when the size of avalanche starting zones are very large, on the order of tens of acres, and/or the lengths of affected highway is long, on the order of hundreds of feet or more, as is the case on State Route 22, on Teton Pass.

As a consequence, WYDOT should remain committed to its effective active avalanche control program on State Route 22, on Teton Pass, subject to continuing to modernize its active avalanche control technologies to be both reliable and timely to operate so as to further reduce traffic delays due to the duration of the active avalanche control portion of the mission. If active avalanche control is the method of choice, cleanup is inevitable, but its duration can be shorten with the implementation of larger and faster front-end loaders and rotary snowplows. Investment in cleanup capacity should keep pace with investment in active avalanche control technology.

To date, investment in personnel resource and professional development for active avalanche control has not kept pace with similar investments in active avalanche control and passive/constructed defense technologies in WYDOT's avalanche control and defense program. This may be rectified in the short term by adding additional, temporary manpower during the winter seasons, though this is not as simple as just more man-hours, but needs to include the temporary addition of individuals with the suite of technical and mountaineer skills needed to perform the duties required for effective active avalanche control, and to do so safely. Active avalanche control personnel work with a great deal of trust amongst themselves, as each individual's safety is inextricably linked to the skills and vigilance of the other personnel. In WYDOT's avalanche control and defense program, amongst others, there is room to improve on capacity building of future avalanche control personnel, and professional development opportunities for existing personnel to continuously improve their requisite skills for these roles. Developing individuals for roles and careers as avalanche control personnel should have an entry point, an established career path, and on-going professional development opportunities.

5.2. What does WYDOT do with a surplus military howitzer

Hardly anything is the answer. The military howitzer is a *low cost redundant* technology in WYDOT's active avalanche control and defense program and provides WYDOT's avalanche control personnel with a valuable personnel development arena, as well.

Reducing reliance on the military weapon as the first technology of choice for active avalanche control is sound. Though tow portable, the military howitzer is slow to deploy for an avalanche control mission. It takes a large (four man) crew to operate. It has environmental impacts from both its explosive residue and resulting ordnance shrapnel. Moreover, the longevity of the military's support for the program is suspect, based on arguments surrounding the remaining supply of useful (low dud rate) ammunition. Noting, though, that this argument for the demise of the military weapons program for active avalanche control has been 'on the table' for decades, with no net action.

The military weapon is capable of meeting every need for active avalanche control on State Route 22, on Teton Pass, in the event that the modern technologies presently found there were to become inoperable. The military weapon cost per shot is the lowest of all active control technologies. Its annual inspection, maintenance and personnel costs to remain proficient as operators are modest, and are present in the existing annual budgets.

Maintaining WYDOT avalanche control personnel's proficiency as military weapons operators includes the annual training/re-training workshop and military liaison briefing required of all avalanche control personnel who operate military weapons for this purpose. Attendance at this annual Avalanche Artillery Users of North America Committee (AAUNAC) meeting [Abromeit, 2004] is one of only a few and a preeminent professional development opportunity for active avalanche control personnel, WYDOT's included.

WYDOT presently has a 35 round supply of ammunition for its howitzer, estimated at 50 percent of the ammunition bunker's capacity [Gorsage, 2018]. This supply should be replenished and maintained at or near full.

5.3. When does passive/constructed avalanche defense make sense?

The implementation of passive/constructed snow supporting structural defense on the RM 151 Avalanche starting zone, on US Route 189/191, south of Jackson, Wyoming, met all the requirements for a site worthy of the expense of passive/constructed avalanche defense. It is in an urbanized area south of Jackson, Wyoming where the regular discharge of active avalanche control explosives would become a nuisance over time. The property adjacent to and on the downhill side of the highway of the RM 151 Avalanche is private and regularly spilling actively controlled avalanches onto it could eventually lead to complex issues with the landowner. US Route 189/191, south of Jackson, Wyoming carries the largest vehicle load in the region, at an average of over 7,014 ADT during the winter months. In a criterion unique to the RM 151 Avalanche starting zone, the starting zone is US Game and Fish critical big game wintering habitat where the regular use of explosives for active avalanche control would be unacceptable with that land use practice. The public is prohibited from entering into the RM 151 Avalanche starting zone during the big game wintering months. Not for the public's safety, but to leave the big game, already stressed by winter, undisturbed.

The RM 151 Avalanche starting zone passive/constructed snow supporting structures cost $2.8 million in 2012, including design and on-site construction inspection. The RM 151 Avalanche starting zone did not avalanche during the extraordinary winter of 2016/2017. To meet this many separate criteria for the implementation of passive/constructed avalanche defense and its attendant costs at a given site is uncommon and is most likely the reason that the RM 151 Avalanche was the first domestic site to see modern passive/constructed avalanche defense implemented in several decades.

To be a candidate site for passive/constructed avalanche defense, in the face of the low cost and effectiveness of active avalanche control, there has to be something or some things that are very 'special' about a given site.

5.4. Recommendations by site

5.4.1. US 189/191, Hoback Canyon

The “Cow-of-the-Woods” and “Calf-of-the-Woods” avalanches on US Route 189/191, in Hoback Canyon, are a special site. These two avalanche paths, the “Cow-of-the-Woods” and “Calf-of-the-Woods” (see Figure 33) are the entire extent of the avalanche hazard on this highway, exceptional winters such as 2016/2017, notwithstanding. Despite the ‘low volume’ nature of this highway, with an average of only 916 ADT in the winter months, US Route 189/191, in Hoback Canyon, should be defended from these avalanches with a deployment of modern passive/constructed snow-net snow supporting structures. See Figure 24 for an example of this passive/constructed avalanche defense technology.

What makes active avalanche control on US Route 189/191, in Hoback Canyon, special is the amount of high value WYDOT active avalanche control personnel resources it garners, especially when State Route 22, on Teton Pass, is in need of attention at the same time. A team of two active avalanche control personnel is fully deployed, if their focus is the higher volume (at 4,430 winter ADT, many of whom are daily commuters) State Route 22, on Teton Pass.

With the avalanche hazard on US Route 189/191, in Hoback Canyon, successfully address with passive/constructed avalanche defense, WYDOT’s existing team of avalanche control personnel are freed up to focusing 100 percent of their efforts on State Route 22, on Teton Pass. Traffic volumes on Teton Pass will continue to grow, while traffic volume growth on US Route 189/191, in Hoback Canyon, can be expected to grow at a slower pace, if at all, in the near future. This places a premium on a focused, technologically advanced, state-of-the-art active avalanche control program on State Route 22, on Teton Pass.

In large part, this can be facilitated if the “Cow-of-the-Woods” and “Calf-of-the-Woods” avalanches on US Route 189/191, in Hoback Canyon, are defended with passive/constructed snow-net snow supporting structures.

Unlike the passive/constructed snow supporting structures in the RM 151 Avalanche starting zone, on US Route 189/191, south of Jackson, Wyoming, there are no USDA Forest Service NEPA Visual Retention issues in the “Cow-of-the-Woods” and “Calf-of-the-Woods” avalanche starting zones, in Hoback Canyon. Rigid snow supporting structures in the RM 151 Avalanche starting zone were chosen to resist the snow’s slow but powerful creep loads that would destroy the vegetative restoration needed to retain pre and post construction visual assets, as required by NEPA, in the RM 151 Avalanche starting zone, as seen from the south Jackson valley floor. This NEPA visual retention requirement is not a criteria that applies to the “Cow-of-the-Woods” and “Calf-of-the-Woods” avalanche starting zones in Hoback Canyon. Flexible snow-nets that do allow for some snow creep would be an acceptable passive/constructed avalanche defense technology for this site.

As a consequence of not having to resist all of the snowpack creep loads, flexible snow-net passive/constructed avalanche defense does not require foundation systems as vigorous as those for rigid snow bridges, like those found in the RM 151 Avalanche starting zone. Because of this, the costs of snow-net passive/constructed avalanche defense is less than the costs for rigid snow bridges by a factor of 20 to 30 percent. Conversely, and very much like the RM 151 Avalanche starting zone, the "Cow-of-the-Woods" and "Calf-of-the-Woods" avalanche starting zones are small, on the order of an acre or two in size, combined. An investment in $2.5 million to $3 million in modern snow-net passive/constructed avalanche defense in the "Cow-of-the-Woods" and "Calf-of-the-Woods" avalanche starting zones above US Route 189/191, in Hoback Canyon, would solve this avalanche problem, and preclude further delays on this highway due to active avalanche control and cleanup. This would free up WYDOT's active avalanche control personnel and cleanup capabilities to focus their attention entirely on State Route 22, on Teton Pass at times when that site is almost certainly in need of active control consideration and efforts.

Passive/constructed avalanche defense in Hoback Canyon would add another $46,000 a year to the annual costs of WYDOT's avalanche control and defense program, based on an estimated 60 year service life for this technology and the amortization of a $2.8 million estimated cost to implement passive/constructed snow-net defense at this site. This would be a 25 percent increase in the seasonal costs for all active control and passive/constructed avalanche defense in WYDOT's program. The projected future seasonal cost of WYDOT's avalanche control and defense program would rise to $225,000.

The $300,000 in TAS O'Bellx® portable gas exploders, presently found on the "Cow-of-the-Woods" and "Calf-of-the-Woods" avalanches in Hoback Canyon, could be redeployed for active avalanche control duty on State Route 22, on Teton Pass, once US Route 189/191, in Hoback Canyon, is successfully defended with the passive/constructed snow-net technology being recommended here.

5.4.2. State Route 22, Teton Pass

The avalanche hazard to State Route 22, on Teton Pass, is being successfully addressed with active avalanche control technologies, despite the irksome delays to motorists caught on one side of the Pass or the other for active avalanche control and cleanup.

Teton Pass will forever garner speculation as to why it is not addressed with passive/constructed avalanche defense technologies. The practical answer, for some time to come, will be the extraordinary costs it would take to address either the entire area of avalanche starting zones above State Route 22 with snow supporting structures, or to cover the entire length of road that would need it with an avalanche shed. The most cost effective solution for avalanche control and defense on State Route 22, on Teton Pass, remains active avalanche control for the foreseeable future. In the face of the enormous cost savings of effective active avalanche control over passive/constructed avalanche defense, and the 4,430 winter ADT, many who are regular commuters, the active avalanche control program in State Route 22, on Teton Pass, should continue to be steered proactively towards state-of-the-art. Investment is warranted in both new modern, remotely fired, portable and fixed gas exploders, and the continued rehabilitation of the existing gas exploder active avalanche control technologies on Teton Pass.

The single aging Avalanche Guard® mortar should be replaced with modern remotely fired, fixed and portable gas exploders. Multiple active avalanche control technologies of various types on a single site complicates procurement of materials and supplies, and leads to inconsistent procedures during active avalanche control missions. Pending implementation of the recommendation for passive/constructed snow-net snow supporting structural defense for the “Cow-of-the-Woods” and “Calf-of-the-Woods” avalanches on US Route 189/191, in Hoback Canyon, the Avalanche Guard®, in Teton Pass, can be replaced at relatively low costs with WYDOT’s two existing portable TAS O’Bellx® gas exploders, presently found in Hoback Canyon.

Avalanche debris clean-up in Teton Pass should be as fast and effective as the modern active avalanche control technology that produced it. Investment in the ‘Cadillac’ of avalanche debris clean-up loaders and rotary snowplows should keep pace with investment in active control technologies. Having this equipment on site at the very moment that active avalanche control is completed saves as much traffic delay time as the control mission or clean-up time themselves.

5.4.3. US Route 89, Snake River Canyon

There are multiple avalanches that attack US Route 89, in the Snake River Canyon, that come from starting zones thousands of feet above the highway from the surrounding Snake River mountain range. The remote, inaccessible nature of these avalanche starting zones makes avalanche hazard forecasting for the Snake River Canyon avalanches even more challenging. Winter traffic volumes on US Route 89, in the Snake River Canyon, are about 75 percent of those on State Route 22, on Teton Pass, at an average of 3,110 ADT. It is the ‘sleeper’ highway avalanche hazard in WYDOT’s avalanche control and defense program. Though sometimes large, the Snake River Canyon avalanches are less common than those on US Route 189/191, in the Hoback Canyon, and on State Route 22, on Teton Pass, and for this reason receive less attention.

There are no active avalanche control or passive/constructed defense technologies deployed for these avalanches. When active avalanche control has been deemed warranted in the Snake River Canyon, heli-bombing has been the method of choice. This has been, and remains a reasonable approach to active avalanche control on US Route 89, in the Snake River Canyon.

Nevertheless, recalling that the safest highway during periods of high avalanche propensity is a closed highway, there is room for additional automated highway closure and dynamic motorist notification capabilities that could be implemented on US Route 89 at both the north and south ends of the Snake River Canyon, in the communities of Hoback Junction and Alpine, Wyoming, respectively. This is especially true if the closure durations are long, as one awaits improving weather to fly a heli-bombing mission, for example. At a minimum, ‘Avalanche Danger, No Stopping or Standing, November through March’ static signage could be increased at the appropriate places where Snake River Canyon avalanches come onto US Route 89.

5.4.5. US Route 189/191, RM 151 Avalanche, south of Jackson, Wyoming

As noted above, the RM 151 Avalanche starting zone above US route 189/191, south of Jackson, Wyoming, with its starting zone passive/constructed snow supporting structural defense is a solved problem for the foreseeable future, but at a cost greater than the more modest costs that active avalanche control would be at this same site.

The RM 151 Avalanche snow supporting structures should be visually inspected on a regular basis. The slow creeping motion of a snowpack leads to large loads on these rigid frames. In addition, the site restoration and revegetation efforts, that included both ground cover and conifer whips, should be inspected regularly for stress and wildlife browsing, and if these are found, actions should be taken to improve the survival of the remaining restoration.

The success of passive/constructed avalanche defense on the RM 151 Avalanche starting zone has helped inform any decision to implement passive/constructed snow-net snow supporting structural avalanche defense for US Route 189/191, in Hoback Canyon. One goal and resulting successful attribute of the RM 151 Avalanche passive/constructed defense was it freed-up WYDOT active avalanche control personnel from having to deal with the RM 151 Avalanche when their attention was already being fully consumed between State Route 22, on Teton Pass and US Route 189/191, in Hoback Canyon.

5.5. Open questions, resources and recommendations for future research

5.5.1. Should WYDOT continue to collect and analyze avalanche program data like these?

The avalanche control and defense cost metrics, and the data that underlies their analysis and consideration found here is not going anywhere. It will remain available, to be mined in the future, if that is deemed warranted. To be valuable as more than the decade long ‘snapshot in time’ that this investigation has been, continuing to collect, reduce and analyze this data needs to be valuable, in near real time, to both WYDOT avalanche control and defense personnel, their immediate supervisors, and statewide transportation planners.

Regardless of whether WYDOT’s avalanche control and defense cost metric data continues to be collected and analyzed, one small detail in the duration of traffic delay times can be captured better right away. The time to complete active avalanche control is one element of traffic delay and the time to clean-up the debris is the other. Those two separate times, which sum to the total traffic delay for one mission of active avalanche control, should be recorded separately.

Additionally, the extended domestic and international community of active avalanche control and defense personnel have collected their mission data in a format that helps them see their successes relative to their active avalanche control attempts [Hamre, 2016]. Though this database does not explicitly examine the costs of active avalanche control, it does speak directly to how practitioners of active avalanche control evaluate the success of their efforts. That alone is valuable for WYDOT’s avalanche control and defense program. Moreover, the regular review of that data by this community of active avalanche control practitioners who are collecting and considering it is a valuable professional development activity. WYDOT is encouraged to continue participating in this data collection and consideration.

5.5.2. There are two different durations of delay – should they be managed differently?

As noted above on reduction in traffic delay, the durations of delay due to active avalanche control tends to be bimodal. There is an average delay that is of short duration - on the order of an hour or less [Yount, 2016].

Conversely and far more infrequent are longer duration delays - on the order of several hours to tens of hours. Under these circumstances, if equipped with timely motorist information on the location and duration of potential delays, motorists may (and perhaps should) seek alternative queuing and lay-up opportunities at locations where there are roadside services. This not only relieves some of the indirect impact of long duration delays on motorists for active avalanche control, but it also avoids queuing motorists on the highway for long periods where there is little or no escape from the elements.

Does WYDOT's avalanche control and defense program presently take full advantage of existing motorist information infrastructure and WYDOT motorist information services personnel? Is there additional motorist information infrastructure and content that could and should be used to better manage long duration traffic delays due to active avalanche control activities? These questions remain open.

5.5.3. Severe storms when 'avalanche control' is no longer a possibility.

There is a cautionary note that goes with active avalanche control. As was the case with the winter of 2016/2017, once widespread regional natural avalanching is underway, the premise that you can control avalanches by bring them down when you want to unto a highway that is temporarily closed is no longer in effect. By definition, naturally occurring avalanches are uncontrolled, and trying to maintain highway serviceability by attempting to actively control over them is no longer a possibility. In these rare, extreme circumstances, alternative avalanche hazard management procedures need to be in place and available to guide both WYDOT's avalanche control program personnel and the statewide transportation system decision makers, all of whom are under stress and potentially operating with competing responsibilities at that juncture. A review of procedures and the planning elements for avalanche control and defense in the face of severe winter storms worthy of emergency designation was not an element of this investigation.

One hallmark of almost all extreme natural disasters is that emergency planning has either never been put into place for such an event and/or if that planning is in place, it has probably never been tested. Extreme winter storms and their ensuing weather emergencies are no exceptions, and if there are mountains and snow in the mix, avalanching onto highways will be part of it.

An approach towards addressing these planning requirements and the resulting procedures for active avalanche control under extreme weather conditions is to see what other entities faced with the same challenge have in place. The TRB Research Synthesis program allows the existing worldwide literature on questions such as this to be investigated for potential starting points, things to consider, and possible solutions. In the same vein, WYDOT participates in a valuable multistate, multitask pooled fund avalanche research investigation, administered by the Colorado DOT [CDOT, 2015]. All the entities of this pooled fund investigation face this same challenge of having effective procedure in place for active avalanche control during extraordinarily severe winter storms and avalanching. Potentially, a research task with this pooled fund investigation on what these procedures are and how they differ and how they are similar would begin to provide some clarity and insight to this overarching active avalanche control challenge.

REFERENCES

Abromeit, D., 2004, United States Military Artillery for Avalanche Control Program: A Brief History in Time, in: Proceedings of the 2004 International Snow Science Workshop, Jackson, Wyoming.

Atwater, M., 1968, The Avalanche Hunters, Macrae Smith.

Brennan, J., 2006, The Evolution of the Avalauncher, in: Proceedings of the 2006 International Snow Science Workshop, Telluride, Colorado.

Bristow, J., 2018, written communique, January 23, 2018.

CDOT, 2015, Transportation Pooled Fund Program - Avalanche Research Pool, http://www.pooledfund.org/Details/Study/586

Decker, R., 2008, Winter Maintenance Research; What You're Looking for in Your Relationship With Researchers, for the Tri-State (Idaho, Utah, Wyoming) Maintenance Engineers' Conference, Jackson, Wyoming.

Decker, R., R. Rice, S. Putnam, S. Singer, 2003, Rural Intelligent Transportation System Natural Hazard Management on Low-Volume Roads, Transportation Research Record, No. 1819.

FHWA, 1968, Plans for Proposed Wyoming Forest Highway 3-2(5) Hoback Canyon, Federal Highway Administration, Region-9, Denver, Colorado, sheet R9-SP-256

Hamre, D., Greene, E., and Margreth, S., 2016, Quantifying the Effectiveness of Active Mitigation on Transportation Corridors, in: Proceedings of the 2016 International Snow Science Workshop, Breckenridge, Colorado.

Hewes, J., Decker, R., Merry, S., and Yount, J., 2010, Implementation of Structural Control Measures for Avalanche Hazard Mitigation Along Transportation Corridors. Transportation Research Record: Journal of the Transportation Research Board, No. 2169.

Hewes, J., Decker, R., and Merry, S., 2013, Design and Construction of Snow Supporting Structures for the Milepost 151 Avalanche, Jackson, Wyoming, in: Proceedings of the 2013 International Snow Science Workshop, Grenoble, France.

Gorsage, B., 2018, written communique, January 17, 2018.

Gorsage, B., 2018, oral communique, 2018.

ITD, 2016, Idaho Transportation Department Road Data, http://itd.idaho.gov/road-data/ .

KDVR, Denver Fox Affiliate, 2015, http://kdvr.com/2014/03/31/2-cdot-avalanche-mitigation-workers-hurt-after-shell-explodes-in-barrel/

Mountaineers Books, 2006, The Avalanche Handbook, 2006.

Margreth, S., 2016, Swiss Federal Institute for Snow and Avalanche Research, oral communique, 2016.

Meier, L., M. Jacquemart, M., Blattmann, B., Arnold, B., 2016, Real-Time Avalanche Detection with Long-Range wide Angle Radars for Road Safety in Zermatt (Switzerland), in: Proceedings of the 2016 International Snow Science Workshop, Breckenridge, Colorado.

NOAA, 2018, Snow Water Equivalents, https://www.wcc.nrcs.usda.gov/webmap .

Perla, R., 1973, Advances in North American Avalanche Technology, USDA Forest Service, Department of Agriculture.

Rice, R., et al (R. Decker), 2002, Avalanche Hazard Reduction for Transportation Corridors Using Real-time Detection and Alarm, Cold Regions Science and Technology, No. 34.

Rice, R., and Decker, R., 2000, A Rural ITS Snow Avalanche Detection and Alarm System, Transportation Research Record, No. 1700.

Root, G., 2008, Battles in the Alps, A History of the Italian Front in the First World War, Publish America.

Schilcher, W., Margreth, S., Sauermoser, S., Skolaut, C., Mölk, M., and Rudolf-Miklau, F., 2015, Structural Avalanche Protection: Defense Systems and Construction Types. In: The Technical Avalanche Protection Handbook, Wiley Blackwell.

Swiss Federal Institute for Snow and Avalanche Research SLF, Bern, Switzerland, 2007, Defense structures in avalanche starting zones Technical guideline as an aid to enforcement (in English). Federal Office for the Environment, FOENWSL.

Ulivieri, G., E. Marchetti, E., Ripepe1, M., Chiambretti, I., Segor, V., 2012, Infrasonic Monitoring of Snow Avalanches in the Alps, in: Proceedings of the 2012 International Snow Science Workshop, Anchorage, Alaska.

WYDOT, 2009, Snow Supporting Structures for Avalanche Hazard Reduction, 151 Avalanche, Highway US 89/191, Jackson, Wyo., https://rosap.ntl.bts.gov/view/dot/17221 .

WYDOT, 2017, 2016/17 Automated Traffic Recorder Report, http://www.dot.state.wy.us/home/planning_projects/Traffic_Data.html.

Yount, J., Decker, R., Rice, R., Wells, L., 2004(a), Reducing Avalanche Hazard to US Route 89/191 in Jackson, Wyoming Using Snow Sails, in Proceedings of the 2004 International Snow Science Workshop, Jackson, Wyoming.

Yount, J., R. Decker, R. Rice, Wells, L., 2004(b), Avalanche Hazard Reduction on US 89/191 (Jackson, Wyoming) using Snow Sails, 5th International Conference on Snow Engineering, Davos, Switzerland.

Yount, J., Naisbitt, A., Scott, E., 2008, Operational Highway Avalanche Forecasting using Infrasonic Avalanche Detection System, in: Proceedings of the 2008 International Snow Science Workshop, Whistler, British Columbia, Canada.

Yount, J., and Gorsage, B., 2016, Evolution of an Avalanche Control Program, in: Proceedings of the 2016 International Snow Science Workshop, Breckenridge, Colorado.

ASSOCIATED REPORTS

Avalanche Hazard Reduction Using the Doppelmayr "Avalanche Guard" Cache and Mortar Technology

Avalanche Hazard Reduction Using The Avalanche Guard: A Cache And Mortar Technology

Avalanche Hazard Reduction Using Wind Drift Disrupters (Snow Sails): Phase I & II

Practical operational implementation of Teton Pass avalanche monitoring infrasound system.

Snow supporting structures for avalanche hazard reduction, 151 Avalanche, US 89/191, Jackson, Wyoming.

Acknowledgements

The author wishes to acknowledge the support of WYDOT's Research Center program, via award #RS06(211), and the assistance of Ms. Enid White, WYDOT Research Center Manager, and her predecessor, Mr. Michael Patritch, now retired, as well as Mr. Tim McDowell, WYDOT Statewide Transportation Planner. Along with these individuals, there are many others who have occupied the roles of WYDOT (Southwest) District 3 Engineer, Maintenance Engineer, Jackson Maintenance Foreman, and Jackson Avalanche Technicians who have been invaluable over the year in seeing that these research activities had the very best chance of success. Mr. Thomas Whelan, a baccalaureate candidate in Civil Engineering at Northern Arizona University brought his insightful programming skills to the challenge of reducing and visualizing the data used in this investigation.

Author's Narrative

This project is the tail end of over two decades of 'putting things up to see what can go wrong' in the arena of novel highway avalanche control and defense technologies, conducted in cooperation with the WYDOT Research Center, the WYDOT Research Advisory Committee (RAC), and personnel from the Jackson Maintenance facility. The goal of this body of research was to use the capacity of WYDOT's research program to 'try lots of things, and anything new', with the caveat that "about half of everything your researchers will try won't work out or turn into anything useful" [Decker, 2002]. Of the successes enjoyed, it was the people, and not just the application of technology to the challenges of mountains, snow and highways that made those possible. This body of work and this project being reported here were dependent on the participation WYDOT personnel to accomplish.

Of note: Even as this report was in final edit with its conclusion, amongst others, that WYDOT has been successful in reducing its dependence on military weapons in their active avalanche control program, Brian Gorsage, senior avalanche control technician with WYDOT in Jackson wrote; "I'm having trouble getting the Avalanche Guard® to fire, so I shot the Howitzer and triggered a large avalanche out of Glory Bowl, on Mt. Glory, below the cliff band." [Gorsage, B., 2018]. This succinctly illuminates the complex mix of expert personnel and the variety of unique skills they possess, and the plethora of modern agile and older redundant technologies that are necessary to have a successful highway avalanche control and defense program.

APPENDICES

APPENDIX A:

All data files are housed at the Wyoming Department of Transportation and may be accessed by contacting the Research Manager at:

Research Manager
5300 Bishop Blvd
Cheyenne WY 82007
307-777-4182