UDOT SR-210

AVALANCHE INFRASTRUCTURE STUDY ABOVE THE TOWN OF ALTA, UT

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Executive Summary

The Utah Department of Transportation (UDOT) SR-210 Town of Alta (TOA) Avalanche Infrastructure Study was conducted to evaluate avalanche hazard mitigation options for avalanche paths affecting SR-210 and the TOA. The study provides UDOT and the project stakeholders with options that will both reduce avalanche hazard and reduce or eliminate Overhead Fire, where artillery is fired over the TOA. Both passive and active controls were reviewed, including: snow sheds, snow nets, deflection and stopping barriers, stopping walls, artillery, Remote Avalanche Control Systems (RACS), helicopter control, hand charging and skier compaction from lift-accessed skiing. Mitigation options were evaluated with the following four main objectives:

1) Reduce the frequency of avalanches reaching the SR-210 highway and TOA;
2) Improve the efficiency of the UDOT avalanche hazard management program by reducing the number and hours of road closures and Inter-lodge restrictions;
3) Improve the safety of workers and public during road closures and explosive control; and
4) Reduce or eliminate the use of 'Overhead Fire' where artillery is fired over the TOA.

Under direction of UDOT, Alta Ski Area personnel fire a 105 mm Howitzer from the Peruvian Ridge gun position at 34 targets between the Cardiff Bowl and Grizzly Cup avalanche paths. During 2003-2012, 714 artillery rounds were fired at these targets, an average of 89 rounds per winter. Many targets have flight trajectories that pass over occupied structures. This practice is discouraged by the US Department of Defense, which has strongly recommended that UDOT find an alternative to the practice of Overhead Fire. Additionally, many structures are located within the 3000' range considered as the danger zone for artillery projectile fragments.

Approximately 152 buildings were identified within the TOA, 81 of which are exposed to Overhead Fire between the Cardiff targets on the west and Michigan targets on the east. Many buildings will have people in them during firing of artillery while Inter-lodge closure is in place. This situation is unique in North America and globally; there may be some areas where Overhead Fire is practiced on a limited scale (e.g. Colorado DOT, which has an extensive artillery program), but not on the scale of the program in Alta.

By implementing the RACS option recommended in this report, targets between the Cardiff and Culps Low avalanche paths could be removed from the artillery control program, resulting in approximately 53 buildings no longer being affected by Overhead Fire.

Avalanche hazard mitigation can be achieved using a variety of approaches, each with differing advantages and disadvantages (Table E1). Two general approaches can be used to mitigate avalanche hazards: active avalanche control, and passive (permanent) avalanche control.

Passive control options for the TOA study area present significant challenges including: high cost, infeasibility due to a deep design snowpack (e.g. for snow nets) and high avalanche velocities (e.g. diversion berms and stopping dams), potential to increase risk to downslope infrastructure (e.g. snow sheds), private land, aesthetics and impact to the environment and recreation. Because of these challenges, extensive passive control measures are not currently recommended as the preferred option for the project area considered in this report. There may be areas that passive control measures could successfully be implemented; however, these would be most effective for protecting high-value residential or commercial structures rather than reducing hazard to the SR-210 roadway. For the TOA, active measures such as RACS provide an more optimized solution that reduces avalanche hazard, but has relatively affordable capital costs that can be incurred over a period of time, if needed.

Table E1. Avalanche control measures.

Active control	Passive control
• Artillery (status quo) • Hand charges • Helicopter control using explosives/Daisy Bell • Remote Avalanche Control Systems (RACS) • Explosive tram • Skier compaction/cutting from ski lift installation	• Snow retaining structures (snow nets) • Snow sheds • Earth berms (stopping dams, diversions) • Catching basin (or check dam system) • Stopping walls • Structural reinforcement

RACS are recommended to replace the artillery targets that result in Overhead Fire. Of the RACS options, the Gazex system is recommended for consideration paths above the TOA, and is evaluated in detail in this report. Wyssen Towers could also be considered for select sites in place of a Gazex (or O'BellX) where terrain presents challenging construction or where a larger radius of effect is needed. Helicopter control could be used to supplement RACS for low frequency targets, using either a Daisy Bell or conventional explosives. Table E2 provides cost estimates for RACS above the TOA. Costs are estimated to be on the order of $3.3-4.7 Million (Gazex and/or Wyssen Tower), with annual O & M costs on the order of $30,000-$60,000.

Table E2. Cost estimate summary for the RACS above the TOA.

Item	Gazex (20 units)		O'BellX (20 units)		Wyssen Tower (17 units)	
	Item Sub Total	*Unit Cost*	Item Sub Total	*Unit Cost*	Item Sub Total	*Unit Cost*
Materials Cost	$1,352,200	*$67,610*	$3,116,000	*$155,800*	$1,955,000	*$115,000*
Installation Cost (low)	$2,163,520	*$108,176*	$1,600,000	*$80,000*	$1,360,000	*$80,000*
Installation Cost (mid)	$2,704,400	*$135,220*	$2,000,000	*$100,000*	$1,700,000	*$100,000*
Installation Cost (high)	$3,380,500	*$169,025*	$2,500,000	*$125,000*	$2,125,000	*$125,000*
Total Cost (low)	$3,515,720	*$175,786*	$4,716,000	*$235,800*	$3,315,000	*$195,000*
Total Cost (mid)	**$4,056,600**	***$202,830***	**$5,116,000**	***$255,800***	**$3,655,000**	***$215,000***
Total Cost (high)	$4,732,700	*$236,635*	$5,616,000	*$280,800*	$4,080,000	*$240,000*
Annual O&M Cost	**$30,500**	***$1,525***	**$30,500**	***$1,525***	**$61,200**	***$3,600***

UDOT installed an Infrasonic system in 2006 to monitor avalanches the White Pine, White Pine Chutes and Little Pine areas. Infrasound provides reliable detection of the onset of natural avalanche cycles, reliably confirms control results, and thus increases public and worker safety. This system has become an indispensable part of the LCC avalanche forecasting program. It is strongly recommended that UDOT continue to develop and expand their avalanche detection network, especially within the paths that affect the TOA. These systems will reduce risk to the public on the road and in the TOA, reduce closure times, and also allow UDOT to optimize closure and control times to less disruptive times, such as the night or early morning. Radar systems have been developed and applied with success to avalanche hazard areas in Europe; these systems should also be considered as an alternative or compliment to infrasound.

1.0 Introduction

The Utah Department of Transportation (UDOT) SR-210 Town of Alta (TOA) Avalanche Infrastructure Study was conducted to evaluate avalanche hazard mitigation options for avalanche paths affecting SR-210 and the TOA. The intent of this study is to provide UDOT, the TOA, and Alta Ski Lifts (ASL) a definitive, clear direction to meet the objectives of reducing the avalanche hazard while reducing or eliminating the practice of firing artillery over the TOA. The study reviews both passive and active controls to reduce avalanche hazard including: snow sheds, snow net systems, earth deflection and stopping barriers, concrete and MSE walls, military artillery, Remote Avalanche Control Systems (RACS), helicopter control, hand charging and skier compaction from lift-accessed skiing. All currently available RACS options were considered, including: Gazex, O'BellX, Wyssen Tower, Avalanche Guard, and Avalanche Master. Mitigation options were evaluated to determine the best option for each avalanche path with consideration of the many constraints and stakeholders in the project area.

Mitigation options were evaluated with the following four main objectives:

1) Reduce the frequency of avalanches reaching the SR-210 highway and TOA;
2) Improve the efficiency of the UDOT avalanche hazard management program by reducing the number and hours of road closures and Inter-lodge restrictions;
3) Improve the safety of workers and public during road closures and explosive avalanche control measures; and
4) Reduce or eliminate the use of 'Overhead Fire' where artillery rounds are fired over the TOA for the purpose of avalanche control, a practice that is strongly discouraged by the U.S. Department of Defense (DOD).

Program improvements should result in an overall reduction of road closure hours per winter, although this may be achieved with an increased number of closures that are shorter in duration (i.e. by using control methods that require less time to implement). Improvements to program efficiency can also be achieved by shifting closure hours to non-peak traffic periods (e.g. overnight or early morning control missions with lower traffic volumes), which reduces the impacts to the normal daytime LLC operations.

The study also considered the effect of each solution on the many different user groups in the terrain around the TOA, including residents, businesses, motorists and backcountry recreationists. The study included stakeholder engagement and partnership with the TOA and ASL, but did not have an element of public engagement.

This report was prepared by Dynamic Avalanche Consulting Ltd. (DAC) for UDOT, with Fehr & Peers (F&P) providing expertise in facilitating project stakeholder meetings, compiling project data and supporting DAC in GIS, visual renderings, field review and reporting. F&P was also responsible for ensuring that the recommendations fit with the overall transportation and development goals within the TOA and the SR-210 highway corridor.

The work presented in this report was completed by Alan Jones, P.Eng. of DAC, with senior support and field review provided by Chris Stethem. Dr. Jordy Hendrikx provided a technical review of this report for DAC. Jon Nepstad of F&P provided senior review of reports, mapping support and consultation based on F&P's extensive experience with traffic planning issues in the Canyon. UDOT avalanche safety staff provided their extensive knowledge of the LCC avalanche program, including long-term program data.

1.1 Methods

The tasks completed and methods used during preparation of this report includes:

- Compiled project data, including: topography; imagery; photographs; avalanche atlases; chair, building and facility locations; snow climate data; and historical avalanche, explosive control and road closure records provided by UDOT and Alta.
- Preliminary scoping of mitigation alternative types and locations.
- Field inspections of avalanche areas and mitigation alternative locations with UDOT personnel. This work reviewed the main control target areas and preliminary mitigation alternative locations based on local topography and historical records.
- Met with key stakeholders from the Town of Alta and Alta ski resort to discuss issues and concerns of each organization.
- Analysis of UDOT artillery control records.
- Analysis of UDOT avalanche occurrence records for 1999-2016.
- Evaluated avalanche risk mitigation options, including: military artillery, snow sheds, snow net systems, preventative road closures, earth deflection and stopping barriers, concrete and MSE walls, RACS, and lift-accessed skiing.
- Evaluated RACS options, including: Gazex, O'BellX, Wyssen Tower, Avalanche Guard, and Avalanche Master, and explosive trams (e.g. CATEX).
- Evaluated recommended RACS option in detail, with consideration of type and size, supply tank and line locations.
- Reviewed potential storage, security, transportation and supply issues.
- Compiled preliminary unit cost estimates provided by manufacturers for the preferred systems, including capital, operations & maintenance costs.
- Compared mitigation alternatives, including a summary table comparing positives/negatives and costs.
- Reporting, summarizing results and recommendations.

Two field investigations were completed of terrain in the project area. The first field review on April 11-14, 2016 was completed on skis by Alan Jones and Chris Stethem, accompanied by UDOT personnel Bill Nalli, Matt McKee, Damian Jackson and Laurie Delaney. The field review was completed under normal spring snowpack conditions. This field trip provided observations of snow distribution and avalanche path configuration, albeit in a relatively thin snowpack winter.

The second field trip was completed by Alan Jones on June 15-16, 2016, accompanied by Bill Nalli and Matt McKee. This inspection was completed with a mostly melted snowpack, which allowed for observation of ground and foundation conditions at each of the potential RACS sites from the Toledo through Culps avalanche paths. Additional observation of runout zones and tracks in these paths was also completed on the second field visit.

2.0 Background

The LCC, or highway SR-210 provides access from the Salt Lake City metropolitan area to the TOA, Alta Ski Area, and Snowbird Ski Resort. UDOT is responsible for maintenance of this state highway, which includes monitoring and control of snow avalanche hazards that affect the road, some of which also affect residential and commercial areas in the TOA.

The previous Little Cottonwood Canyon SR-210 Transportation Study (F&P, 2006) provided a comprehensive study of avalanche risk and management in LCC, including: analysis of risk to the highway from avalanches and ways to reduce the dependence on artillery; evaluation of risk reduction measures and associated costs; and provision of a blueprint for future avalanche risk reduction projects. F&P (2006) evaluated avalanche hazards for the entire LCC highway corridor, which includes 64 avalanche paths and the notably very active and problematic White Pine and Hellgate-Superior avalanche areas.

The study presented in this report focusses only on avalanche areas that affect parts of SR-210 within the TOA, which includes nine main avalanche paths, and several subsidiary paths. This report builds from the work presented in F&P (2006), and is intended to provide a more detailed site specific assessment of avalanche hazard management in the TOA.

2.1 Study Area Avalanche Paths

The study area assessed in this report includes avalanche paths within the TOA road section, which extends from the East Hellgate avalanche path to the end of the state maintained highway near the Grizzly avalanche path, at the start of the Albion Basin Road (Figure 1). However, the Hellgate-Superior avalanche area is currently being addressed separately by UDOT, so is not included in the scope of this report. The avalanche paths assessed in this report start in the west at the Cardiff path (Mile 11.6), and continue eastward to the Grizzly Gulch avalanche path (Mile 12.6) over a distance of approximately one mile.

Figure 1. Town of Alta avalanche Infrastructure Study project area, approximately indicated between the black lines (Source: UDOT).

Table 1. TOA avalanche paths reviewed in this report.

Cardiff
Toledo
Flagstaff Shoulder
Flagstaff (Binx's)
Flagstaff Mine
Emma 1
Emma 2
Emma 3
Emma 4
Emma 5 (Culps West)
Culps
Davenport
Grizzly
Grizzly Cup

Avalanche paths discussed in this report are shown in Table 1, with the ten paths that are provided a greater level of evaluation highlighted in bold. The attached Avalanche Atlas map (Appendix A) shows approximate outlines of the avalanche paths assessed in this report.

Cardiff is currently being evaluated separately for UDOT for the installation of Gazex, but was reviewed in this report because it shares a common runout zone with Toledo. Davenport, Grizzly and Grizzly Cup all merge into the common Grizzly Gulch, but are of sufficiently low frequency to SR-210 and the TOA such that they do not require detailed evaluation in this report. The other paths (Toledo to Culps) all have a significant effect on the SR-210 and the TOA such that they are provided detailed evaluation of mitigation alternatives in this report.

The avalanche paths reviewed affect SR-210 with an estimated return period between 4 and greater than 25 years. These TOA paths affect the road less frequently than paths in the full LCC corridor, where avalanches have typically affected the road 33 times per winter (F&P, 2006). However, the risk of avalanches reaching the road in the TOA section can be higher due to the presence of numerous residential and commercial buildings in the tracks and runout zones of avalanche paths, and the large concentrations of public and workers in this area.

Historically, there have been many avalanche fatalities in the Alta area, mostly during the early mining development period in the late 1800's. The active artillery control program initiated by the US Forest Service (USFS) in the 1940's and continued to date by UDOT has reduced the hazard in the TOA, and limited the effect to structures in the town to a few destructive events, the last of which occurred in 2002 when an avalanche impacted the Peruvian Lodge.

2.2 Avalanche Control Above the TOA Using Artillery

Avalanche control is currently conducted for the paths above the TOA using artillery fired from the Peruvian Ridge gun position in the Alta Ski Area. This is occasionally supplemented by explosives deployed from helicopter, but artillery remains the primary method used by UDOT.

UDOT applies frequent artillery control measures in order to produce frequent, small to medium sized avalanches (e.g. Size D2 to D3) rather than allow snow to build such that larger avalanches (e.g. Size D4) are possible. Although this strategy results in higher closure numbers per winter, it reduces the length of road closures by avoiding large avalanche deposits on the road; this also reduces the likelihood of avalanches impacting structures in the TOA.

Under direction of UDOT, Alta Ski Area personnel fire a 105 mm Howitzer from the Peruvian Ridge gun position at 34 targets between Cardiff Bowl (Target P51) and Grizzly Cup (Target P97). During 2003-2012, 714 artillery rounds were fired at these 34 targets, an average of 89 rounds per winter. Many of these targets have flight trajectories that pass over occupied structures. This practice is discouraged by the USDOD, which has strongly recommended that

UDOT find an alternative to the practice of Overhead Fire. In addition to the Overhead Fire issue, some structures are located within the 3000’ range which is typically considered as the danger zone for projectile fragments following detonation of an explosive round.

Projectile fragments could also present a risk to the public (i.e. skiers) present in a closed area during an artillery control mission. UDOT secures the explosive danger zone prior to control, but there is increasing skier traffic in the area which makes this an increasingly difficult closure to enforce, and thus an increasing risk. The terrain above the TOA is particularly difficult for UDOT to secure compared to other parts of LCC due to the full-time presence of skiers in the town during winter, and with access possible from the north side of the ridge from the Big Cottonwood Canyon. Groups of keen ‘dawn patrol’ skiers are increasingly a challenge since they make a point of skiing during the early, pre-dawn morning hours and the late, early evening dusk hours, precisely at the times when UDOT may wish to conduct control when there are lower traffic volumes on the road. Artillery control can be conducted at night, but this provides additional operational challenges such as visual confirmation of control results and availability of staffing for control and road closures.

In addition to the problems associated with Overhead Fire and projectile fragment zones, there is also the potential for overshooting a ridge, either due to operator error or an equipment malfunction, either with the gun or the projectile. UDOT had an overshoot occur at Provo Canyon in 2005 due to operator error, which impacted a residential area and damaged a residence. Although UDOT takes all precautions necessary to avoid such events, there remains a potential risk for a similar event in the future.

When UDOT completes artillery control and during periods of elevated avalanche hazard, Inter-lodge Travel and Maximum Security (evacuating certain sections of exposed buildings and relocating the occupants to areas considered to be safer) restrictions are put into effect in the TOA by authority of the Town Marshall upon consultation with UDOT avalanche forecasters. Reduction of the duration of Inter-lodge restrictions will benefit the community and businesses, although restrictions will still be needed with any of the active mitigation alternatives discussed in this report.

The safety issues with artillery control discussed above highlight the need for UDOT to seek alternative avalanche hazard mitigation measures in the paths located above the TOA.

2.3 Traffic Volumes in LCC

F&P (2006) completed a comprehensive review of traffic volumes on SR-210 that concluded that traffic volumes in LCC had remained at an Average Annual Daily Traffic (AADT) of approximately 5500 vehicles per day (vpd) during 1996-2006. However, traffic congestion remains a problem during peak days and peak times, typically peaking at 8000 vpd during weekends in February and March. Higher peaks may occur on holidays and weekends, with volumes increasing up to the 9,000-12,000 vpd range.

Hourly traffic volumes are subject to large increases during the morning eastbound period (8:00-9:00 am) and afternoon westbound period (4:00 pm) as skiers arrive and depart the valley. Peak volume days, and particularly peak volume hours, greatly increase the risk in the canyon as there is almost a continuous line of slow moving vehicles during these times, and a greatly increased likelihood that an avalanche that impacts the open highway will impact a vehicle.

UDOT provided additional updated data that shows that the relatively constant traffic volume of approximately 5500 vpd observed during 1996-2006 was valid for the period up to 2013 (Table 2 and Figure 2); however, there is a distinct upwards volume trend noted during 2014 and 2015. This two-year period is currently too short to indicate a permanently upward volume trend, but certainly highlights a distinct upwards step, similar to that which can be observed from 1986 to 1987 (3910 vpd jumped up to 4985 vpd). It is important to note that the data in Figure 2 reflects the full year of traffic volumes in LCC (i.e. January-December), not just the winter.

Table 2. Average Annual Daily Traffic (AADT) during 1981-2015.

Year	AADT	Year	AADT
1981	3,645	1999	5,655
1982	3,565	2000	5,820
1983	3,770	2001	5,530
1984	3,740	2002	5,390
1985	4,085	2003	5,435
1986	3,910	2004	5,625
1987	4,985	2005	5,775
1988	4,990	2006	5,510
1989	5,100	2007	5,510
1990	5,175	2008	5,480
1991	5,100	2009	5,430
1992	5,625	2010	5,575
1993	5,680	2011	5,405
1994	5,970	2012	5,325
1995	5,745	2013	5,560
1996	5,890	2014	5,950
1997	5,970	2015	6,535
1998	5,470		

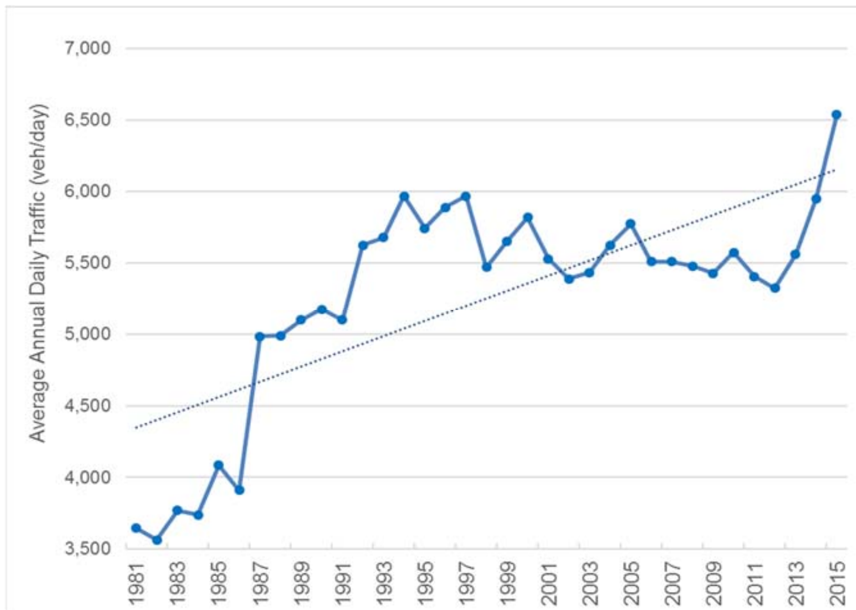


Figure 2. AADT during 1981-2015. Blue dotted line shows a linear trendline during this period, highlighting the upward trending traffic volumes in LCC. Source: UDOT, Site ID 90684, Station 035-1225.

Looking at winter (December through March) data only provides additional insight into traffic volumes in LCC, and changes in recent years (Figure 3). Average December through March volumes had an overall decrease from 2006 to 2012 (7,646 vpd down to 6,208 vpd), but have since recovered and increased steadily up to 7,269 vpd. This is below the 2006 peak, but indicates an overall increasing trend in traffic volumes during the winter since 2012.

Another notable trend in Figure 3 is the much higher traffic volumes observed on winter weekends, which have remained mostly above 7000 vpd, and have increased significantly to 8,230 vpd in 2015. This is consistent with the 1996-2006 F&P (2006) estimate of 8000 vpd during winter weekends.

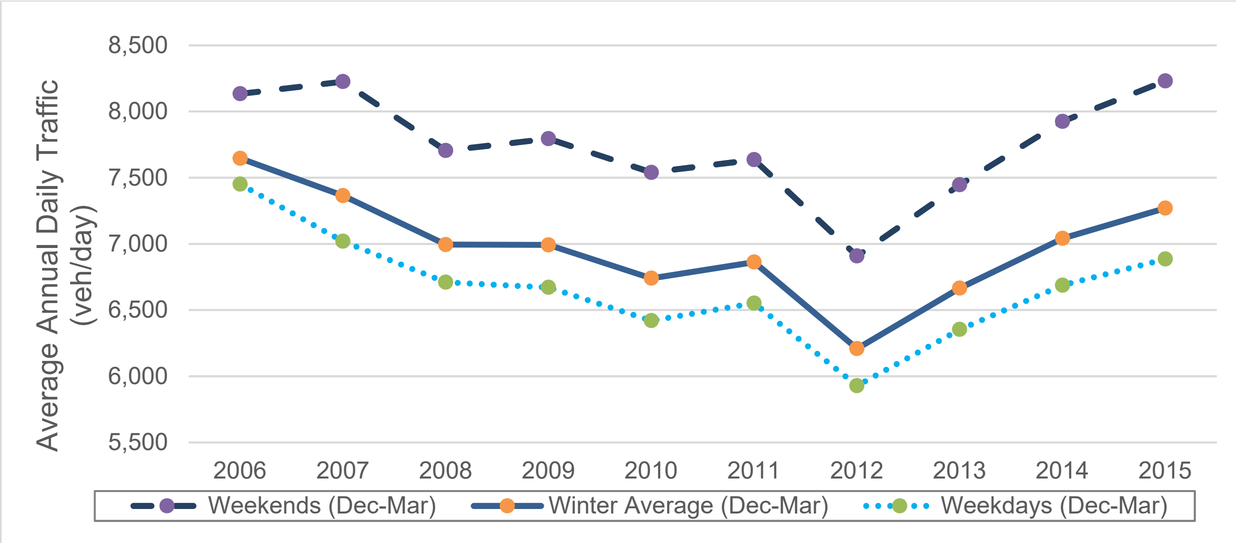


Figure 3. Winter Average Daily Traffic (December-March), analysed for weekends, weekdays, and all winter days. Source: UDOT Station 317, Mouth of Little Cottonwood Canyon, SLC.

Figure 4 highlights the trend in peak hourly traffic volumes, which is increasingly becoming an issue in the Canyon, both in terms of the higher peak volumes (and thus increased avalanche risk), as well as the increasing number of days with peak traffic volumes. For example, the highest observed hourly volume was steady at approximately 1370 vehicles during 2006-2013, but has jumped to greater than 1600 vehicles in 2014 and 2015, which is a 20% increase in peak volume. This trend is similar for the 10^{th} to 100^{th} highest hourly volumes, with an approximate 11-12% volume increase in 2014 and 2015 compared to previous years.

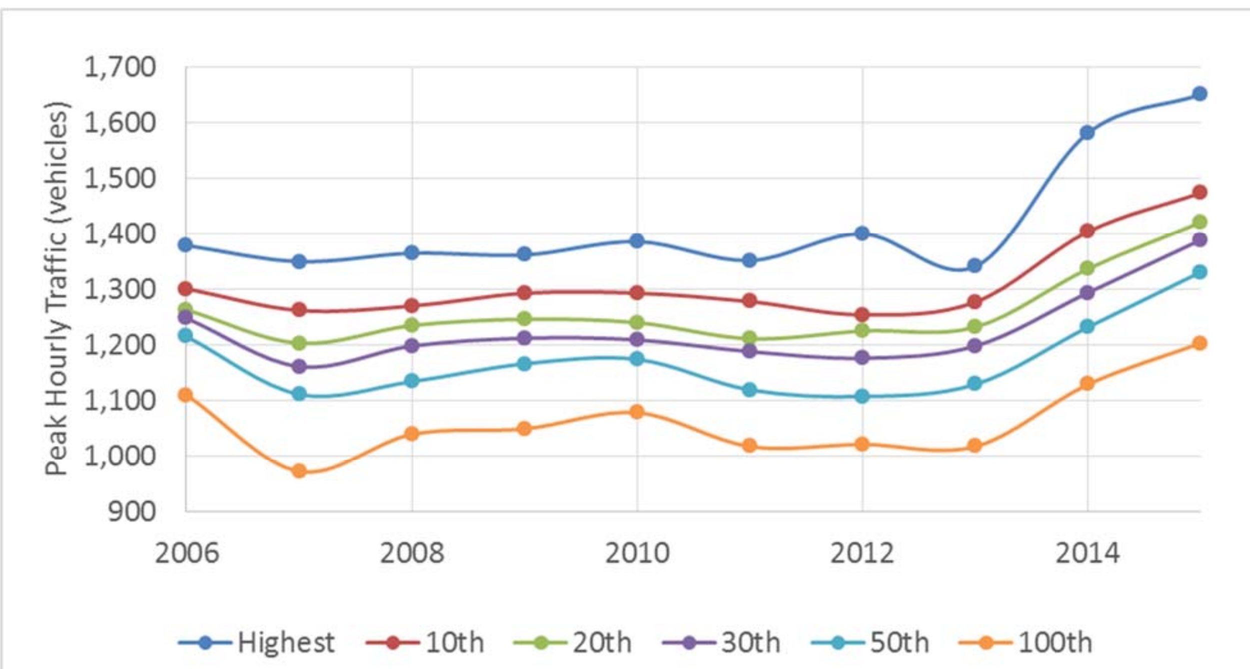


Figure 4. Peak hourly traffic volumes in LCC during 2006-2015.

The trends observed in Figures 2-4 that relate to avalanche hazard can be summarized as:

- Winter traffic volumes have increased since 2012, but volumes are currently (as of 2015) comparable to what they were in 2006 (~ 8000-8500 vpd on weekends, ~7000-7500 vpd on weekdays) when the F&P (2006) report was completed.
- Overall, there is an increasing traffic volume trend noticeable in 2014-2015 that is reasonable to assume will continue to increase.
- Higher peak volumes of approximately 9,000-12,000 vpd can be expected on holidays and key winter weekends.
- Peak hourly traffic volumes have increased in recent years, notably by approximately 20% in 2014 and 2015 compared to 2006-2013. This implies both an increase in the number of vehicles during peak hours, as well as an increase in the number of days during the winter that experience peak volumes.

2.4 Avalanche Hazard Index

F&P (2006) evaluated the Avalanche Hazard Index (AHI) for the LCC to understand the risk to people travelling in vehicles on the road, and to evaluate alternatives to reduce the hazard. It is not in the scope of the current report to re-evaluate AHI, but a brief discussion is provided below for additional context and understanding of changes in AHI.

F&P (2006) estimated the AHI for the entire LCC to be 1045 (Figure 5), which is classified in the Very High hazard category. That value was based on historical avalanche occurrence observations during 1972-2005. This assumes no avalanche control and free-moving traffic of 7000 vpd. Inclusion of the Superior Bypass reduces the baseline AHI to 482, a reduction of approximately 50%.

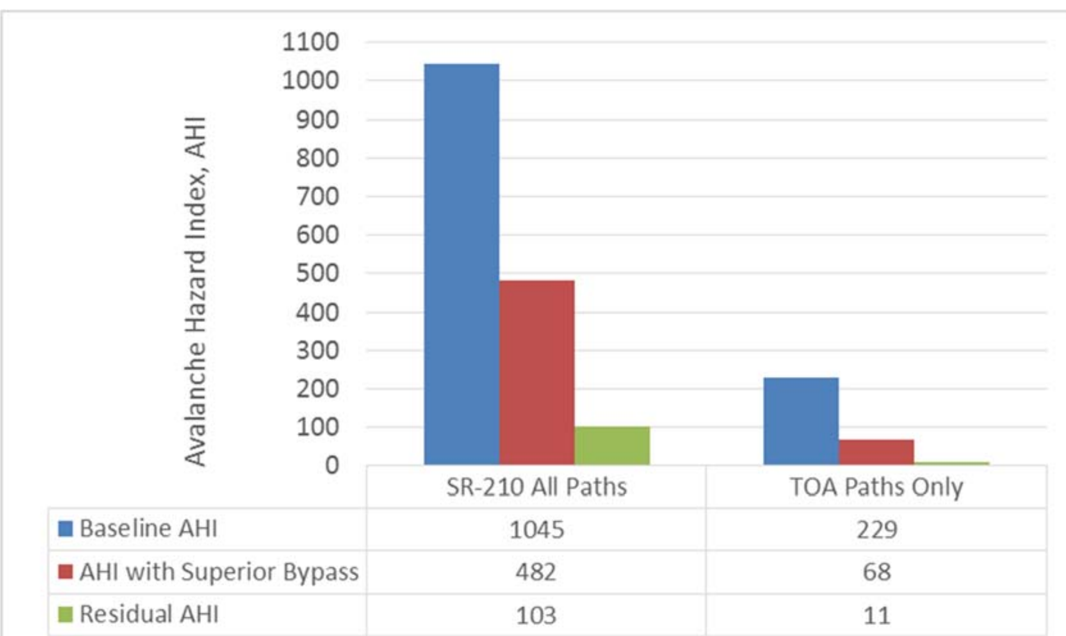


Figure 5. Summary of Avalanche Hazard Index **(**AHI) and Residual AHI (RHI) estimates provided in F&P (2006), assuming 7000 vpd.

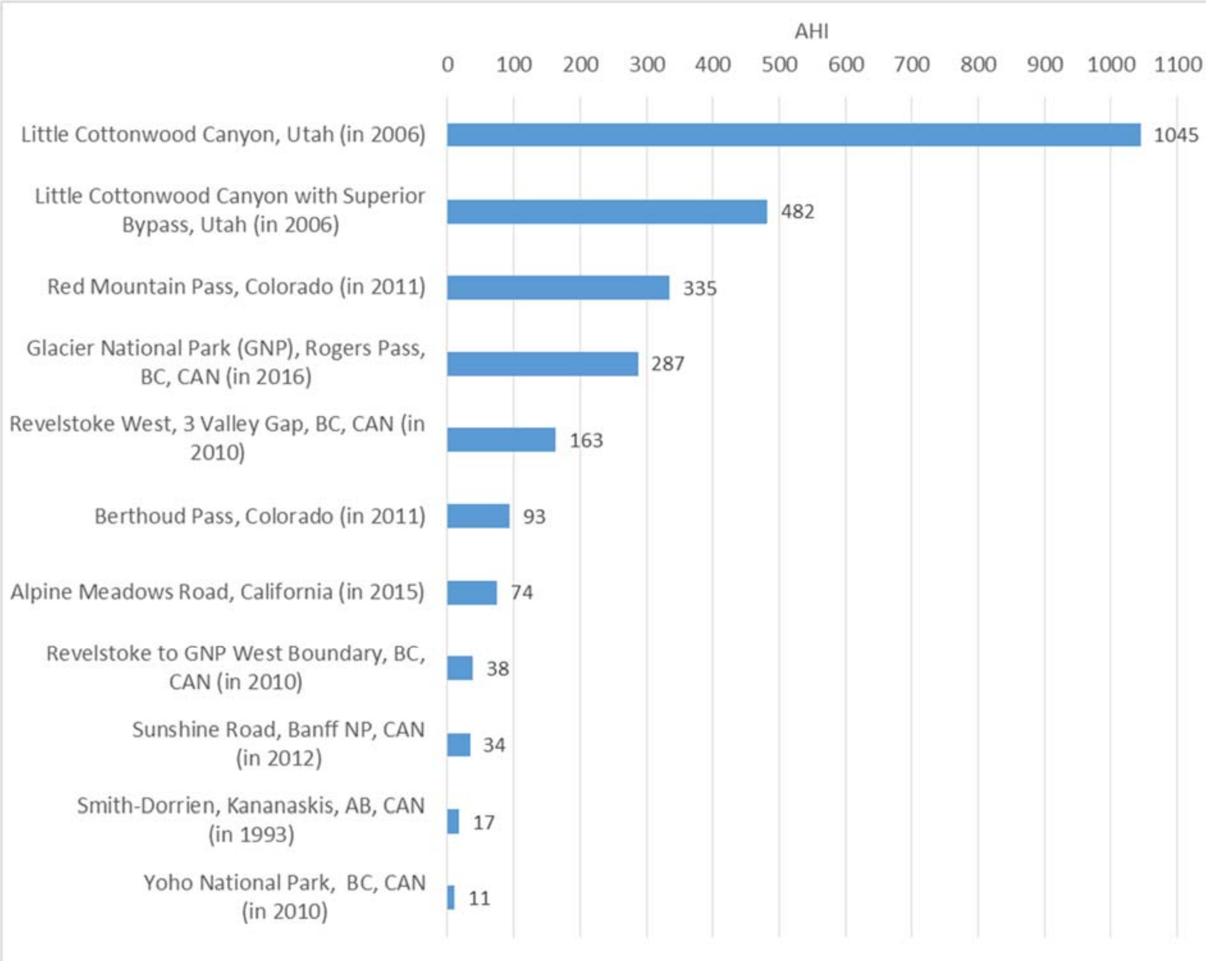


Figure 6. Reported AHI for various North American Highways affected by avalanche hazards.

With explosive avalanche control applied and the Superior Bypass in effect, the AHI is further reduced to 103 (High category), or 10% of the uncontrolled hazard. This represents the hazard to vehicles on the open road, and was derived using historical records of light and deep avalanches observed to reach the open road, which is the 'Residual Avalanche Hazard', or RHI.

These AHI values represents the highest risk avalanche highway corridor in North America (Figure 6), and ideally should be reduced to a value of less than 40 (or even lower, if possible), which is the Moderate category. This may be difficult to achieve in LCC considering the high frequency of avalanches, increasing traffic volumes and challenges implementing permanent mitigation measures such as berms and snow sheds (to be discussed later in this report).

Even with this relatively high hazard, there has not been an avalanche fatality on the LCC highway since 1952, which is reflective of the dedication and high skill of the UDOT avalanche forecast team in forecasting avalanches and implementing hazard reduction measures.

In the TOA study area, AHI was rated in 2006 as 229 out of a total of 1045, which accounts for about 22% of the hazard in the LCC. By putting the Superior Bypass in effect, the hazard to traffic from Hellgate-Superior was removed so that there was no waiting traffic in the TOA paths due to hazards in the Hellgate-Superior section. This resulted in an AHI in the TOA section of approximately 11 out of 103, or 10% of the resulting AHI in the entire LCC with avalanche control applied. Note that this analysis does not account for avalanche hazards from the Blackjack path, which affect the Superior Bypass.

Based on this analysis, it is very apparent that the avalanche risk management program implemented by UDOT has greatly reduced the avalanche hazard in the TOA area, but it is still considered higher than what would be typically be considered acceptable by international standards, and the hazard to structures and people within the TOA still remains.

As discussed in F&P (2006), AHI can be reduced by changing how avalanches affect the road (i.e. changing the frequency and/or magnitude), or by changing the traffic characteristics. Roadway measures include active measures (e.g. artillery, RACS, infrasound, forecasting) and passive measures (e.g. snow sheds, diversion berms, snow nets, realignment), which are options that are evaluated in this report.

Traffic measures include demand reduction, parking management, information systems, traffic flow, parking lot metering, and incident management. These measures reduce the number of people exposed to avalanche hazards, which reduces risk. Discussion of traffic measures is beyond the scope of this report; we focus on mitigation to reduce the hazard to the roadway.

Updating of the AHI is beyond the scope of the work in this report. If one were to assume that the average traffic volumes have not changed significantly since 2006, then the AHI would stay relatively the same. Increasing traffic volume proportionately increases the AHI, but this is compounded by hazard to waiting traffic, so it is not a linear relationship. Additionally, the increase in peak traffic volumes will also result in an increased AHI that is not accurately reflected by using “average” traffic volumes.

Independent of any changes in traffic volume, any reduction in the AHI presented in F&P (2006) will have resulted from improved avalanche forecasting methods and/or improved avalanche control methods. That is the case for parts of LCC, where significant changes to the program since 2006 include installation of a series of Gazex and O’BellX RACS, and implementation of an infrasonic avalanche detection system. Since 2006 there have been no fundamental changes in the way that avalanche hazards are managed in the avalanche paths above the TOA (i.e. no significant changes to avalanche forecasting or artillery control methods), so the avalanche hazard and risk in this area is assumed to be similar to the value presented in 2006.

3.0 Snowfall and Snowpack Summary

Two weather stations in the project area provide high quality, long term data for analysis of the local snow climate: Alta Guard Station and Alta Collins. The Alta Guard Station is maintained by UDOT, and is located near the UDOT Guard Station at 8799'. This station provides one of the longest continuous datasets in the region, spanning from 1945-2016 (72 years).

The Alta Ski Area patrol maintains the Alta Collins station which is located at 9664' near the Mid-Mountain Station of the Collins chair. Data from 1981 to 2016 (36 years) were reviewed.

Annual snowfall data (November-April) and annual maximum snowpack height from the Alta Guard Station were fit to a Gumbel (Extreme Value Type 1) distributions to determine theoretical annual maximum snowfall and snowpack height for 10, 30, 50 and 100-year return periods (Table 3). No consideration was given to the potential impacts of climate change in modifying future snowfall. The Collins station was also analysed for maximum snowpack height.

Table 3. Summary of annual snowfall (HN) and maximum annual snowpack height (HS) data at the Alta Guard Station and Alta Collins stations.

	Alta Guard Station (8799')		**Alta Collins (9664')**	**TOA avalanche path starting zones estimate, 9,200-10,500'** (15% increase above Alta Guard Station)
	Snowfall, HN (Inches)	Snowpack Height, HS (Inches)	Snowpack Height, HS (Inches)	Snowpack Height, HS (Inches)
	Observed Values			
Number of years	70	70	36	~
Mean Annual Maximum	487	125	151	144
Standard Deviation	102	25	35	~
Maximum Observed	744*	218	236	~
	Statistical Estimates			
10-year	620	158	197	182
30-year	709	180	228	207
50-year	750	190	242	219
100-year	806	204	261	235

*Maximum observed excludes 1994-1995 winter due to data discrepancy.

Average annual snowfall at the Alta Guard Station is 487 inches, with a maximum observed of 744 inches in winter 1983-84, which represents an approximately 50-year return period snowfall winter. Winter 1994-95 was excluded due to data collection discrepancies noted by UDOT.

Maximum annual snowpack height values shown in Table 3 illustrate the deep snowpack at Alta, averaging between 125 inches at Alta Guard Station up to 151 inches at Collins Mid-Station. Maximum snowpack winters were observed at Alta Guard Station in 1975 (218 inches) and in 1983 (236 inches) at Collins. The 1975 Alta Guard snowpack exceeded the 100-year snowpack height (between a 100 and 300-year event, statistically); the observed maximum Collins snowpack of 236 inches was representative of a 30-50 year event.

It can be observed in Table 3 that Collins has a substantially higher annual maximum snowpack height due to the higher elevation, with the mean annual maximum 21% higher than at Alta Guard Station. The statistical maxima range between 25% higher (10-year) and 28% higher (100-year) when comparing Collins to Alta Guard Station maximum annual snowpacks.

These deep snowpack heights are representative for elevations between 8800 and 9700 ft, which is lower than the majority of the starting zone areas for the paths above the TOA, which are near 9,200' to 10,500'. However, the starting zones above the TOA are south facing and strongly affected by sun and wind, while Collins is more sheltered, northerly facing and in a favourable orographic uplift area, which increases snowfall.

Based on the experience of UDOT avalanche safety personnel, the maximum annual snowpack in the TOA path starting zones (e.g. the Emma's) is typically higher than at Alta Guard Station but lower than Collins. Since long-term starting zone snowpack height data were not available, a 15% increase in snowpack height was assumed to be a reasonable, expert-judgement based value for starting zones above TOA. This results in an average annual maximum of 144 inches, with an assumed 50 to 100-year maximum snowpack heights in the starting zone areas above the TOA in the range of 218-235 inches (18-20 ft) (Table 3). This is close to the 100-year snowpack height of 218 inches observed at the Alta Guard Station in 1974-1975.

This information is useful for determining the expected frequency of use of mitigation systems, as well as optimal heights for placement of systems above the snowpack. In particular, RACS like Gazex need to be placed at a height above the expected snowpack height to provide optimal performance during below average winters (i.e. thinner snowpack) and during maximum winters when there is a deep snowpack. In deep snowpack areas, shelters will need to be placed sufficiently high above the design snowpack to avoid frequent snow removal. Alternatively, shelters can be placed on a wind-exposed ridgeline where snow is scoured. This consideration is especially important for the smaller autonomous chest systems for the Gazex, which otherwise will be inaccessible during the winter.

These maximum snowpack estimates are also needed for estimating the design height of snow nets that could be considered for permanent mitigation of avalanche hazards. Snow net design typically considers the 100-year maximum snowpack height in the starting zone elevation, plus any consideration for increased snowpack height due to wind loading of snow.

4.0 Avalanche Hazard Overview

This section provides an overview of the avalanche paths in the TOA project area, discussion of avalanche hazard to SR-210 and structures in the TOA, and a discussion of avalanche return period to the road and notable events. This review is based on historical data provided by UDOT from 1993-2016 plus some older historical events, AHI information presented in F&P (2006), and various newspaper articles and personnel accounts. The intent of this information is to put avalanche hazard in the TOA into context, both in terms of the current avalanche hazard mitigation program and potential hazard reduction with mitigation alternatives.

4.1 Avalanche Path Descriptions

The avalanches paths evaluated in this report span the area from Cardiff on the west to Davenport on the east (Figure 7). These paths are defined based on their unique runout location onto the SR-210, but actually represent at least 25 unique start zones that merge in common track sections, and have complex flow characteristics in the tracks and runout zones.

Figure 7. Avalanche paths located above the Town of Alta. UDOT images and annotations.

All of these paths have the potential to reach the SR-210 and many have affected or have the potential to affect infrastructure and buildings in the TOA.

Table 4 provides a summary of path characteristics, including vertical drop, length of path, and current artillery targets. Path descriptions and summaries of notable events are provided below.

Table 4. Overview of avalanche paths in the Town of Alta project area.

Primary Path	Secondary Path/Target	Vertical drop to SR-210 (ft)	Path Length to SR-210 (ft)	Artillery Targets
Cardiff				P51, P53, P55
Toledo	Toledo Bowl Toledo Bowl High Toledo Bowl Right Toledo Face Toledo Chute	1710-1840	4410-4700	P57, P59, P61, P63, P65, P67
Flagstaff Low	Flagstaff Low	1110	2870	P69, P70
Flagstaff	Flagstaff Flagstaff Shoulder Flagstaff Right Binx's Folly Emma 1 Left	1390-1650	3700-4090	P71, P73, P75, P77, P78, P79, P80
Flagstaff Mine	Flagstaff Mine	1070	3010	
Emma 1	Emma 1 Emma 1 Right Emma 1 Right Low	1100-1460	2820-3690	P81, P83, P84
Emma 2 & 3	Emma 2 Emma 2 Right Emma 2 Right Low Emma 3 Emma 3 Right	980-1510	2490-3620	P85, P86, P88, P90
Emma 4	Emma 4	1170	2510	P89
Emma 5 (Culps West)	Emma 5 (Culps West)	910	2000	
Culps	Culps Culps Low	730-1190	1840-2660	P91, P92
Davenport	Davenport Davenport Left	950-1110	2360-2960	P93

Cardiff Bowl

Cardiff Bowl is a large alpine bowl with multiple northeast through south facing start zones that have average slope angles near 36-38°. The north side of the bowl has a steep headwall with an average slope angle of 50-60°. A large bench at the bottom of the upper bowl is 200-400' wide. Below this bench the slope angle increases, and the track steepens to approximately 15-30°. Below 9100', the track becomes confined in a gully which continues to the SR-210. The Wildcat parking area is in the Cardiff runout zone below SR-210; this path may also have potential to affect the Peruvian Lodge at its western extremity.

Notable events:

- Dec. 30, 1973, avalanche from Cardiff narrowly missed the Peruvian Lodge, buried 15 parked cars. An avalanche from Flagstaff stuck the Alta Lodge on the same date.
- Dec. 23, 2014, an artillery triggered avalanche was noted by UDOT to "dribble onto white line of roadside".

Other than these records, most avalanches from Cardiff Bowl have had historically limited effect to the highway in more recent years (e.g. since 1993).

Toledo Bowl

Toledo Bowl is a large alpine bowl with multiple start zones that includes aspects extending from east through southwest. The majority of the upper bowl has slope angles of 35-45° while the lower center of the bowl is generally 20-30° with a few steeper short sections. Below 9350' the avalanche path becomes a confined gully which continues down to the highway elevation in a common runout zone with Cardiff.

Notable events:

- Jan. 12, 1997, an avalanche hit a transformer and knocked out power to the lodge.
- March 14, 2002, an artillery triggered avalanche impacted the lodge causing damage to the building as well as damage to 14 vehicles in the parking lot.
- Avalanches have recently reached the parking area in front of Peruvian Lodge, including events on January 21, 1999 and December 26, 2008.

Flagstaff Low

Flagstaff Low has a relatively low start zone elevation that starts near 9900' at the lower end of the ridge that divides Toledo Bowl from Flagstaff. The start zone is a relatively planar slope with a southeast aspect and an average slope angle of 35°. The track crosses several road benches and flows through a shallow gully east of the Alta Guard Station. The UDOT Garage and Our Lady of the Snows Center and the historic Atwater Study Plot are located in the path above the SR-210, and avalanches have the potential to continue past the road towards the Goldminers Daughter Lodge.

Notable events:

- Flagstaff Low has historically flowed over the UDOT Garage and reached the road, although there are no records of it reaching the road since 1993 (24 years).
- The former UDOT avalanche program director, Liam Fitzgerald, moved the Alta Guard weather plot from the Atwater site in 1997 due to potential avalanche hazard; the plot was over-run by an avalanche in that same year (within 400 feet of SR-210, or less).

Flagstaff

Flagstaff path includes several unique start zones which flow into three main gullies, which then converge into a single gully near 9000' elevation. The westernmost gully captures avalanche flows from the Flagstaff Shoulder, Flagstaff, and Flagstaff High targets. Flagstaff and Flagstaff High are large planar slopes while Flagstaff Shoulder is a smaller shoulder feature off the main ridge. These three start zones have southeast aspects with average slope angles of 35-39°.

The center gully includes the Flagstaff High Right and Flagstaff Low Right targets. Flagstaff High Right has a southeast aspect and an average slope angle of 35°. Flagstaff Low Right is a shallow bowl with southeast to south aspects and an average slope angle of 35°.

The easternmost of the three gullies captures avalanches from the Binx’s Folly and Emma 1 Left start zones. Binx’s Folly is a broad gully with southeast to south aspects and an average slope angle of 34°. Emma 1 Left is a planar slope with a south aspect and an average slope angle of 34°, and flows into Flagstaff rather than Emma 1, as its name implies.

Notable events:

- Dec. 30, 1973, avalanche flowed into the Alta Lodge, buried a guest (non-fatally) and damaged vehicles in the parking lot. This avalanche was also reported to have blown out the windows of an old church (the current Photo Haus) located upslope of SR-210, and filled the interior with snow.
- May 1983, a wet avalanche destroyed this same church, which was then relocated.
- Jan. 15, 1995, Debris with vegetation hit road just west of firehouse. Two vehicles hit. Artillery controlled, reportedly from Binx’s Folly start zone.
- Jan. 17, 1998, Avalanche hit the road in two places. Reached Flagstaff parking lot.

<u>Flagstaff Mine</u>

The Flagstaff Mine path is not noted as a regular avalanche path affecting SR-210, but was identified by UDOT forecasters as a path as having history of affecting the road. It is identified in this report as a distinct path since it has an independent start zone and distinct gully at the road.

Flagstaff Mine has a relatively low start zone elevation that starts at the end of the ridge that divides the main Flagstaff start zones and the Emma 1 start zones. The start zone has a subtle cross-slope convexity with southeast to south aspects and an average slope angle of 35°. The track starts as a shallow gully which becomes a well-confined gully below 8850' elevation. There are no buildings in the runout area but there is a parking area located immediately below the SR-210, as well as a bus stop located on the upslope side of the road within the path boundaries. Avalanche hazard to this bus stop was previously assessed by UDOT personnel.

There are no artillery targets for the Flagstaff Mine path and no records of artillery being used between 2004 and 2012. There are also no records of avalanches reaching the road in this path between 1999 and 2016, but at least one avalanche reached the road prior to 1999.

Notable events:

- Jan. 15, 1995, Debris with vegetation hit road just west of firehouse. Two vehicles hit. Recorded in the UDOT occurrence records as artillery controlled in the Binx’s start zone, but was noted by UDOT as occurring in Flagstaff Mine based on the description.

Emma 1

Emma 1 includes several gullies in the start zone that converge near 9400' elevation. These gullies have southeast to southwest aspects and average slope angles of 34-36°. There are three main starting zones (Emma 1, Emma 1 Right, Emma 1 Right Low) that merge into a common gully near 9500' elevation, and continues in a well-confined gully to SR-210.

The TOA has a water reservoir structure located below a road near 8900'; there is a stacked rock diversion wall that is 220' long and typically 5-7' high (average approximately 6'). This wall was reportedly constructed to keep avalanches flowing to the east in the gully, but avalanches have continued straight from this point directly to the Snowpine Lodge.

Notable events:

- 1939, the top floor of the partially constructed Snowpine Lodge was ripped off by an avalanche.
- Snowpine Lodge was also reportedly impacted during the 1970's.

No recent events (post-1993) were recorded in the avalanche occurrence database.

Emma 2/3

Emma 2 includes the Emma 2 and Emma 2 Right start zones, which are both distinct gullies with southeast through southwest aspects and have average slope angles of 34-36°. Emma 3 has two start zones Emma 3 and Emma 3 Right, with southeast through southwest aspects and an average slope angle of 35°. Emma 2 and Emma 3 share an avalanche track which merge near 8980' elevation, and are thus grouped together for avalanches reaching SR-210.

The TOA has a water reservoir access point structure at the western edge of the path at the SR-210 road which could be affected by avalanches; the path also affects parking areas.

There are no occurrence records of avalanches reaching the SR-210 road during the period of 1993-2016, but it has reached the road prior to this period. UDOT reported that this path reached within 50 feet of the road in 2013.

Emma 4

The Emma 4 start zone includes a distinct shallow gully with south through southwest aspects and an average slope angle of 37°. The track becomes well confined below around 9200' elevation and remains well confined to the road. There are no buildings located in the Emma 4 runout zone, but there are parking areas below the SR-210 which can be affected.

Notable events:

- Since 1993, Emma 4 had one recorded avalanche reach the road and the Grizzly and Albion parking lots. Otherwise, there were no recorded avalanches on the road.

Emma 5 (Culps West)

Emma 5, which is also known as Culps West, is a smaller path that starts near 9700' at the ridge that divides Emma 4 and Culps start zones. The start zone is a planar slope with a south aspect and an average slope angle of 37°. The start zone is sparsely treed, while the track becomes progressively more treed towards SR-210, with avalanches flowing either in the gully or through the trees.

There are three houses located in the avalanche track above the SR-210. The easternmost of these residences is located below a 150' long by 10-15' high earthfill diversion berm, and is structurally reinforced for avalanche impacts. The two residences located along the western edge of the path are also structurally reinforced for avalanche impacts. Below the SR-210, a parking area may be affected by this path. There are no artillery targets in the Emma 5/Culps West path and no record of artillery being used between 2004 and 2012.

Notable events:

- Feb. 4, 2008, avalanche impacted 'Highmark' house, noted as Culps in occurrence records, but confirmed by UDOT that it ran in Emma 5.
- In 2011, a natural avalanche was reported to have impacted one of the houses in the track above the SR-210.
- Feb. 8, 2014, an avalanche was reported to have overrun the avalanche diversion berm.

Culps

The Culps start zone is a shallow bowl with south through southwest aspects and an average slope angle of 36°. The upper track is a shallow gully which becomes confined near 9100' elevation and continues as a well-confined gully to the road. Below the SR-210 is the Albion parking lot, the Albion Day Lodge, Albion ticket office, and the Little Grizzly Lift.

Notable events:

- Jan. 15, 1995, four cars were damaged by an avalanche that did not reach the Albion parking lot.
- Jan. 12, 1997 an powder avalanche impacted the Albion Grill and damaged cars in the parking lot.
- Jan. 18, 1998, crossed the parking lot and damaged cars.
- Feb. 4, 2008, impacted 11 cars, powder reached the Albion Grill.

Davenport

Davenport has two main start zones with unique tracks that converge at 8800' elevation and continue in a deeply incised gully to the SR-210. The main Davenport start zone is a shallow bowl with southeast through south aspects and an average slope angle of 36°. The Davenport Left start zone is lower than the main start zone and is a planar slope with a south aspect and an average slope angle of 36°. Below the SR-210 is the Albion parking lot, the Albion Day Lodge, Albion ticket office, and the Little Grizzly Lift.

During 1999 to 2016, there are no records of avalanches reaching the SR-210, but historically this path has reached the road on an infrequent basis.

Davenport shares a common runout zone with the Grizzly, Grizzly Cup and Michigan paths, which all converge in the deeply incised Grizzly Gulch above about 9000' elevation. These paths do not have a modern history of affecting the SR-210, and are only very infrequently controlled by artillery. For those reasons, these paths are not further analysed in this report.

4.2 Avalanche Occurrence Records

Avalanche occurrence records were provided by UDOT for observed natural and artificially (explosive) triggered avalanches. The data used as inputs for the AHI in the F&P (2006) study spanned the period of 1972 to 2005, supplemented by information from the Highway Safety Plan (UDOT, 2002) and interviews with key personnel. A summary is provided below of return period inputs by path used in the F&P (2006) AHI work, with a new analysis of the 1993-2016 occurrence records to assess notable events or changes to frequency observed in the data.

Table 5 shows the 1972-2005 data used in F&P (2006) separated into light snow avalanches (≤ 3 ft deposit on the road) and deep snow avalanches (> 3 ft deposit on the road), as per the AHI method. The widths on the road are averages of deposits recorded on the road. The light snow and deep snow avalanches were combined into a single value to provide an overall estimate of potentially destructive avalanches reaching SR-210. Values range from a return period of 2.2 years for Emma 1 up to 20 years for Flagstaff Shoulder/Low.

Table 5. Summary of avalanche path return period, T (years) and Width (ft) to SR-210 used as inputs into the F&P (2006) AHI calculations. Data from 1972-2005.

Path(s)	Light Avalanches		Deep Avalanches		Combined Deep+Light,
	T (Years)	Width (ft)	T (Years)	Width (ft)	T (Years)
Cardiff Toledo	100	175	4	375	3.8
Flagstaff Shoulder/Low	100	75	25	150	20
Flagstaff Face / Emma	15	85	5.8	216	4.2
Emma 1	2.6	110	15	250	2.2
Emma 2, 3	30	100	15	190	10
Emma 4	15	80	10	160	6
Culps	7	65	4.8	130	2.8
Grizzly	10	53	3	130	7.5

Table 6 provides a summary of avalanches that reached SR-210 in the TOA avalanche area during the 24-year period of 1993-2016. There were 13 avalanches noted in the dataset, all of which were artillery controlled.

Table 6. Avalanches recorded as reaching SR-210 during 1993-2016 (UDOT data).

Path(s)	Year	Comments
Cardiff	~	No recorded avalanches to SR-210.
Toledo	1993 1998 1999 2002 2008	Dribble on road, west of Red's Avalanche hit the Peruvian Lodge 10' deep x 300' wide on road, reached Peruvian Lodge parking 8' deep x 700' wide on road, damaged Peruvian Lodge and 10 vehicles 5' deep x 200' wide deposit on road, stopped before barrier at Peruvian
Flagstaff Shoulder	~	No recorded avalanches to SR-210.
Flagstaff Face/Emma	1995 1998	Debris with vegetation west of firehouse. 2 vehicles hit. From Flagstaff Mine path. Avalanche hit the road in two places. Reached Flagstaff parking lot
Emma 1	~	No recorded avalanches to SR-210
Emma 2, 3	~	No recorded avalanches to SR-210
Emma 4	1993	Destroyed trees and cars. Ran across Grizzly and Albion lots
Emma 5 (Culps West)	2008	Hit the Highmark House. Impacted 11 parked cars. Powder cloud to Albion Grill 4' deep x 190' wide on road
Culps	1995 1997 1998	Damaged 4 cars. Did not reach Albion Lot Dust Cloud hit the Albion Grill. Cars damaged in lot Crossed parking lot damaging cars
Davenport	~	No recorded avalanches to SR-210

Table 7 presents the estimated return period of avalanches reaching SR-210 with the current artillery control program. These estimates are based on the more recent avalanche occurrence data (1993-2016) which better reflect the current program than the 1973-2005 dataset. Because there were relatively few avalanches that reached the road during this period, the return period values in years are significantly higher than the values assumed in the 1973-2005 dataset.

Table 7. Summary of avalanche path return period, T (years) to SR-210 with avalanche control. Based on UDOT avalanche occurrence data from 1993-2016.

Path(s)	Return Period, T (Years) of avalanches reaching SR-210
Cardiff	>25
Toledo	5
Flagstaff Shoulder	>25
Flagstaff Face / Emma	10
Emma 1	>25
Emma 2, 3	>25
Emma 4	20
Emma 5 (Culps West)	20
Culps	5
Davenport	>25

Figure 8 compares the return period of avalanches reaching SR-210 from the 1973-2005 and 1993-2016 datasets. Several important changes can be noted between these two datasets:

- The Toledo and Culps paths (T= 5-6 years) stand out as the paths most frequently affecting the road, which is relatively unchanged from the values previously assumed (T= 3-4 years) in the AHI.
- Flagstaff Shoulder Low return period has remained comparable (T=20 to 25 years), it still only infrequently affects the road.
- Flagstaff return period to the road has increased from 4 years to 10 years, which is reflective of only 2 avalanches noted as reaching the road in the more recent dataset.
- The Emma 1 return period has changed significantly between datasets, which was 2.2 years in the older dataset and has increased to 20 years in the recent data. This is an important change that reflects the lack of recent records of Emma 1 reaching the road. Any unrecorded observations of avalanches reaching the road could reduce this return period; it was assumed that the occurrence dataset was complete.
- Emma 2/3, Emma 4 and Grizzly/Davenport have all increased significantly from 6-10 year return periods in the older dataset to 20-25 years in the recent dataset. This reflects no avalanches or 1 avalanche reaching the road in the 24-year dataset.

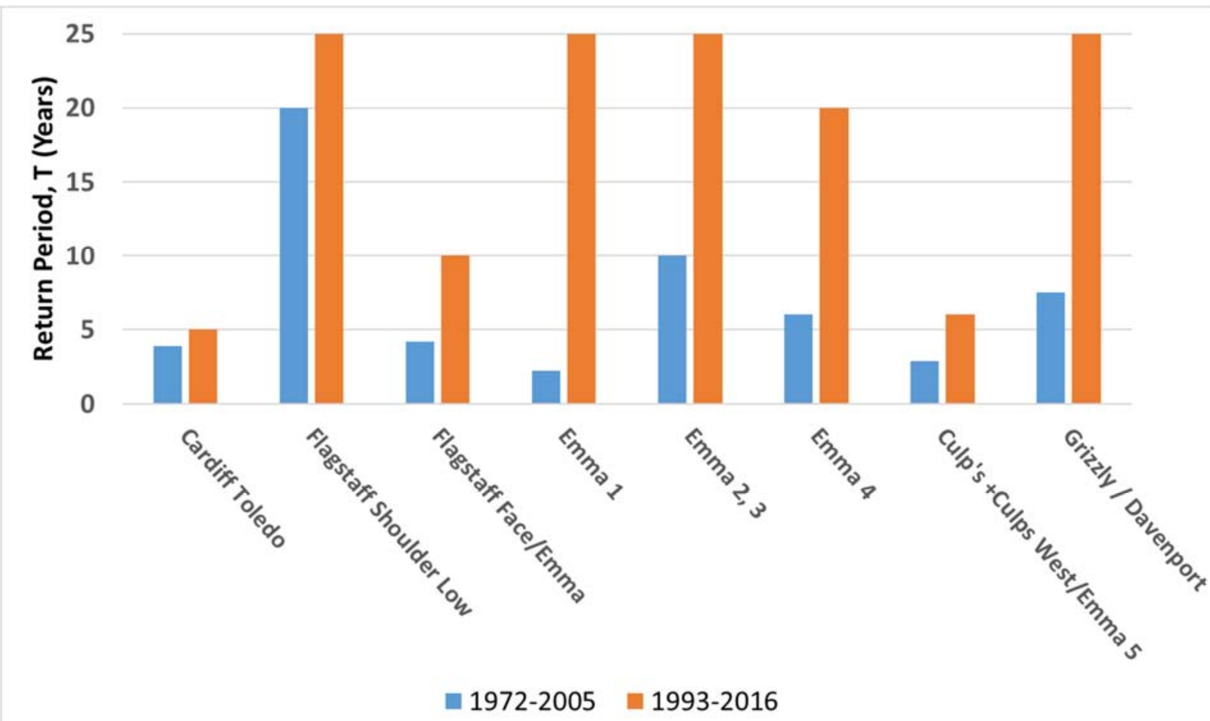


Figure 8. Comparison of return period of avalanches reaching SR-210 for the two datasets: 1973-2005 and 1993-2016. Cardiff/Toledo are combined for both datasets. Also note that 25-year maximum is a nominal value that represents no observed avalanche to road in > 24 years.

This overall increase in return period (or conversely, decrease in frequency) of avalanches reaching the road reflects highly on the skill and effectiveness of the UDOT avalanche forecast and control program in reducing risk to the public on the road and in the TOA. There may be some seasonal effects within the dataset that could change the path return periods, but the

1993-2016 dataset is sufficiently long (24 years) to provide a reliable estimate of return periods that reflects the current avalanche management program.

4.3 Annual Artillery Rounds Summary for P-Ridge Gun

UDOT provided annual artillery usage records for the period of 1999-2014, as well as more detailed target-specific artillery records for 2003-2012. These records were analysed and a summary of this data is provided below.

Figure 9 shows artillery round usage for the P-Ridge gun position by year from 1999 to 2014 (blue bars). During this period, a total of 4652 rounds were fired from the P-Ridge gun, an average of 194 rounds per winter. The trend line shows a slightly increasing usage trend from around 175 rounds/winter in 1991 to over 200 rounds/winter in recent years, which is skewed somewhat by several active winters (e.g. 2005, 2009, 2011). The 1993 and 2005 winters stand out as very active winters, with 344 and 323 rounds fired from P-Ridge gun.

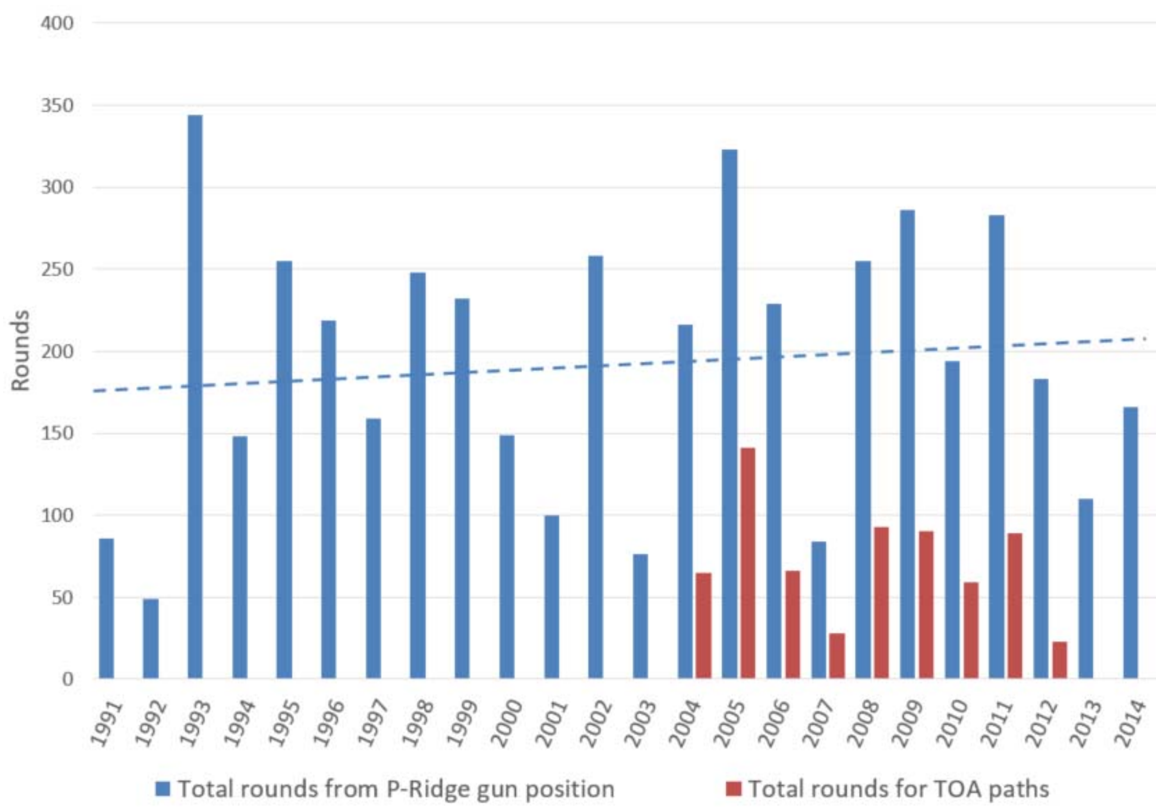


Figure 9. Total rounds fired from P-Ridge gun position (1991-2014) and total rounds fired in the TOA paths/targets (P51-P97) (2004-2012).

The red bars show the artillery round usage for the targets that fall within the current TOA study area, which extends from Cardiff (target P51) to the Grizzly Cup (P97). This dataset was provided for 2004-2012 (nine winters), during which time a total of 714 rounds were fired above the TOA in the study area, an average of 79 rounds per winter. The rounds fired specifically at Targets P51 to P97 account for approximately 32% of the total P-Ridge artillery rounds fired.

UDOT provided an estimate of annual expenses for UDOT military weapons program for the 2012-13 winter. The average cost per round was estimated to be $91.55, plus a transport cost of $5.47 per round, a total of $97.02 per round. There are additional annual costs (e.g. USFS agreement, weapon maintenance, US Army fees, training and operations), but these are costs that are common to the P-Ridge gun for other targets as well as the Valley Gun.

Assuming a unit cost of $97.02 per round and an average of 79 rounds per winter specific to the TOA artillery targets, average annual costs for firing at these targets is estimated on the order of $7,500. In a maximum winter when approximately 146 rounds are fired into the targets above the TOA, artillery round costs are estimated on the order of $13,000. Realized savings from these costs could be applied comparably to annual operating costs for other mitigation methods such as RACS.

The cost estimates provided above do not account for the personnel costs to deliver the rounds to the targets; they only account for consumable costs. Personnel costs would be incremental to control at other targets with the P-Ridge gun, but could be in the range of several thousand dollars per year, accounting for time procuring, storing, loading and firing rounds specific to the TOA targets. Thus, a reasonable combined (consumables and labour) average cost for artillery control may be on the order of $10,000-15,000 per winter specific to the TOA targets, which is approximately 10-15% of the $100,000 estimated annual expenses for the UDOT military weapons program (data supplied by UDOT).

4.4 Artillery Rounds by Target for the TOA Paths/Targets

Figure 10 summarizes annual artillery round usage by target for the paths within the TOA, specifically Cardiff (Target P51) to Grizzly Cup (P97). Blue bars show average number of rounds fired at each target, red bars show maximum annual rounds from 2004-2012. Similarly, Figure 11 summarizes the same data with targets grouped by path.

From this data, the following important points can be summarized:

- Toledo Face (P61) is the most frequently shot target, any RACS system will need to accommodate on average 11 shots per winter, or 15 shots in a maximum winter.
- Other targets that receive notably frequent control include Flagstaff Shoulder (P71), Flagstaff High (P75), Emma 1 (P81) and Culps (P91). These targets are fired annually 5-8 times in an average winter, and 10-13 times in a maximum winter.
- The above two points illustrate that RACS systems should ideally provide up to 10 shots per winter, but several of the key locations may need 10-15 shots, or redundancy with other targets within the same path.
- Several of the targets are very infrequently shot (e.g. Toledo Target P68, Flagstaff targets P78, Emma 1 Targets P80 and P82, Grizzly Targets P95 and P97); these targets may not necessarily need mitigation by systems such as RACS (e.g. Daisy Bell, helicopter control or artillery could be used occasionally at these locations).
- The Flagstaff Low P69 target is considered a critical target despite the low frequency, so some consideration must be given how important a specific target is to the overall risk management, not just the frequency of use in the artillery usage records. From the

records, it can be observed that Flagstaff Low (P69 and P71) were fired upon a combined 6 times during the 2010-2011 winter, so a method such as helicopter control or Daisy Bell may not be considered sufficiently reliable for this target during some active winters.

- In Figure 10, Davenport and Grizzly paths stand out as low use target areas, which are considered suitable for occasional explosive control by means other than RACS (e.g. continue using artillery, Daisy Bell, helicopter control).

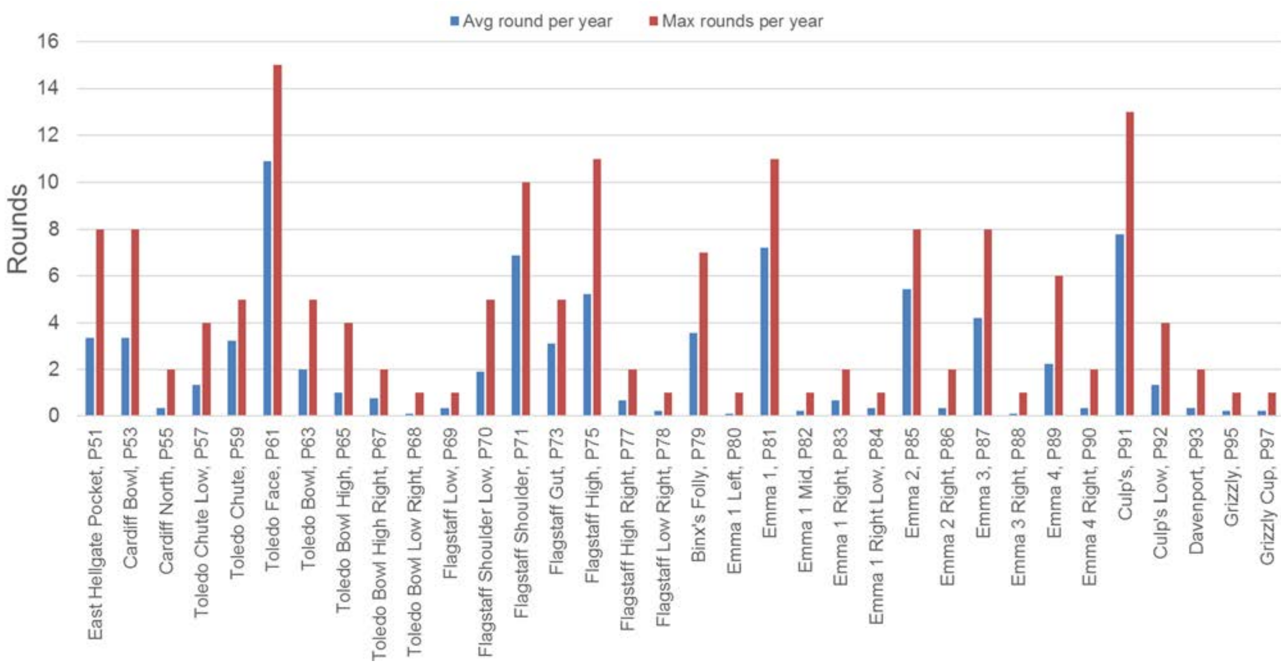


Figure 10. Annual artillery rounds shot by target for the TOA paths (Targets P51-P97), 2004-2012 data.

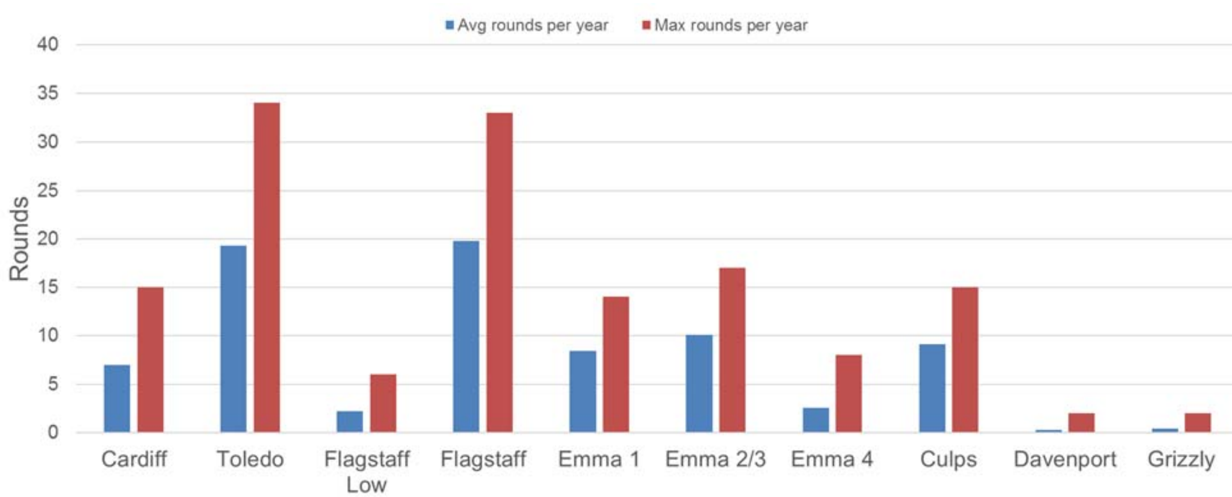


Figure 11. Annual artillery rounds by path, for the paths above the TOA, 2004-2012 data.

4.5 Overhead Fire in the Town of Alta

One of the biggest issues that is driving changes to the UDOT artillery program in LCC is the practice of 'Overhead Fire', which involves firing live artillery ammunition over occupied buildings. According to UDOT documentation, "this practice is a cause of great concern to the Army which supplies the ammunition and weapons used in avalanche control programs nation-wide. The Army is strongly recommending to UDOT to find an alternative to the practice of Overhead Fire".

A GIS file that was supplied by the Town of Alta included 168 buildings, 152 of which are located within the TOA boundary. An estimated 81 of these buildings are exposed to Overhead Fire between targets P53 (Cardiff) on the west to P99 (Michigan) on the east. Many of these buildings will have people in them during firing of the Howitzer while an Inter-lodge closure is in place. This is a unique situation in North America and globally; there may be some areas where Overhead Fire is practiced on a limited scale (e.g. Colorado DOT, which has an extensive artillery program), but not on the scale of the program in Alta.

The Artillery Overfire Reduction map included in the Appendix illustrates the scope of the problem. The upper map shows the current situation, with buildings in the TOA exposed to overfire highlighted in red.

By implementing the Gazex RACS option discussed later in this report, Targets P51 (Cardiff) through P92 (Culps Low) could be removed from the artillery control program, resulting in 53 buildings no longer being affected by Overhead Fire. The lower map in the Artillery Overfire Reduction map in Appendix A highlights in black the buildings that would no longer be exposed to overfire following implementation of the planned UDOT RACS program (recommendations from this report, as well as installations in Cardiff and Hellgate).

Continuing artillery control in the infrequently used Targets P93 to P99 (Davenport, Grizzly, Michigan) would result in residual overfire for 16 buildings. Future construction of RACS for these targets, or control with alternate methods (e.g. Daisy Bell, helicopter control) would result in removal of 69 of 81 buildings from overfire (85% removed).

The remaining 12 buildings are located in trajectories for control of the Hellgate path, which is not addressed in the current report, but is part of a separate avalanche hazard mitigation program currently being proposed by UDOT.

5.0 Mitigation Options

Avalanche hazard mitigation can be achieved using a variety of approaches and systems, each with differing advantages and disadvantages.

Two general approaches can be used to mitigate avalanche hazards:

- Active avalanche control
- Passive (permanent) avalanche control

Active control options that could be considered for the TOA area include:

- Artillery (status quo)
- Hand charges
- Helicopter control using explosives and/or Daisy Bell
- Remote Avalanche Control Systems (RACS)
- Explosive tram (e.g. CATEX from Montaz Equipment)
- Skier compaction/ski cutting resulting from ski lift installation

Avalanche detection systems such as infrasound and radar are also discussed below as a method to improve avalanche forecasting and reduce closures.

RACS options can be further divided into the following systems that are currently available on the market:

- Gazex (TAS, France)
- O'BellX (TAS, France)
- Wyssen Tower (Wyssen Avalanche Control, Switzerland)
- Avalanche Guard/Master (Inauen Schatti/CIL, Switzerland)

Active avalanche mitigation options that are considered need to provide a remotely operated explosive blast to avalanche starting zones, have a high degree of reliability, and ideally allow for redundancy to account for partial system failure.

Gazex and O'BellX systems provide a remotely detonated gas explosion from a permanent, fixed location in the avalanche starting zone. UDOT already has an extensive network of Gazex and several O'BellX systems. The Wyssen Tower and Avalanche Guard/Master systems are essentially secure, explosive deployment boxes with pre-armed explosives that are delivered into starting zones from a fixed location.

The CATEX system differs from the other systems in that it delivers conventional explosives to the avalanche starting zone via an aerial tramway system.

All of these systems are modern, commercially available systems with a reasonably long history of use at numerous locations in North America and/or internationally. These systems were developed and are constructed in Europe (France and Switzerland), but have North American representatives and distribution networks.

Passive control options that could be considered for the TOA area include:

- Snow retaining structures (various suppliers, e.g. TAS, Macaferri, Trumer, Geobrugg)
- Snow sheds
- Earth berms (stopping dams or diversion berms)
- Catching basin (or check dam system)
- Stopping walls
- Structural reinforcement

In general, passive control systems are divided into systems that either hold the snow in place in the starting zone (i.e. snow nets), protect areas by diverting or stopping avalanche flow in the track or runout zone (e.g. snow sheds, diversion berms, catching basins, stopping walls), or those that protect the structure itself (structural reinforcement).

While passive systems in the runout zone present a viable solution for some roadways or development areas, in the case of the TOA there is limited opportunity for these due the steep incline of the paths, and the proximity of the road and structures to the paths. Avalanches in Alta can be very fast moving and turbulent and thus difficult to divert or stop, limiting the feasibility of options such as earth berms.

F&P (2006) provided comprehensive background material on many of the options described above, including proposed concepts with locations and estimated costs. However, that study focussed on the areas in the LCC such as White Pine and Hellgate-Superior. Similar concepts as applied to the paths above the TOA are discussed in the following sections.

5.1 Passive (Permanent) Mitigation Options

5.1.1 Snow Supporting Structures (Snow Nets and Fences)

Figure 12. An example snow net installation at 35 Mile Bluffs, BC, Canada. Photo: A. Jones.

Snow supporting structures are a permanent passive mitigation option (Figure 12). Rather than attempt to release the snow, and remove the instability from the starting zone with active control, snow supporting structures are placed in the starting zone to hold the snow and prevent avalanches. The concept of a snow supporting structure has been used for more than 50 years in the European Alps with good success. They have historically been constructed using a combination of timber or steel framing materials using a variety of designs, with either horizontal or vertical slats. Modern snow supporting structures are now typically constructed using anchored wire nets, with either one single anchor point, or with supporting posts. These have been recently installed in the USA (e.g. Snoqualmie Pass) and Canada (e.g. Kicking Horse Canyon, 35 Mile Bluffs, Glacier National Park in Rogers Pass).

The key considerations for snow nets include the expected 100-year return period snow depth (expected to exceed 235 inches), as the structure's design height should not be over-topped; the ground cover (for anchoring options); the area / distance needed, and the number of rows needed. While snow nets present an attractive permanent solution, they are often considered cost prohibitive for lower traffic volume roads, or areas with multiple avalanche paths.

Snow nets could be applied in any of the starting zone areas above the TOA, but there are many disadvantages with this sort of system, notwithstanding the very high cost. There are also important considerations of aesthetics, as they will significantly alter the visual aspects of the landscape, and they exclude skiing activities.

The Snow Net Areas Map in the Appendix shows each of the avalanche paths above the TOA with a slope class map that identifies avalanche the primary avalanche starting zones with slopes in excess of 30 degrees. From this figure it's apparent that very large areas covered with snow nets would be needed in these starting zones to completely prevent avalanche formation. For example, the smallest of the starting zone areas such as Emma 5 (Culps West) or Flagstaff Low cover areas of 0.91 Hectares (Ha) (2.2 acres) and 1.7 Ha (4.1 acres), respectively.

F&P (2006) provided an approximate unit cost of $0.5 Million per Ha (2.471 acres) for flexible net structures and $1.0 Million per Ha for rigid fences. Using a standard CPI Inflation Calculator, results in $0.6 Million/Ha for flexible nets and $1.2 Million/Ha for rigid fences projected to 2016. However, the two recent major snow net projects in North America were constructed at substantially higher costs. The recently completed Snoqualmie, WA project was constructed at a cost of approximately $2 Million/Ha for nets ranging in height from 9.8' to 13.1'. A snow net project in Rogers Pass, BC currently underway is projected to cost $3.0 Million/Ha for 11.5' to 13.1' high nets, measured perpendicular to the slope. Both projects are located in challenging, steep terrain, which present more difficult construction conditions than those at Alta. However, deep snow depths in Alta may require rigid structures, or the highest flexible snow nets that are currently available. Thus, a conservative unit cost of $2.5 Million /Ha is assumed for the Alta starting zones; actual costs could be lower based on refined, site-specific assessment.

At Alta, the 100-year design snowpack height at the Alta Collins Station (9664 ft) is 261 inches (21.8 ft) of snowpack, while the maximum observed was 236 inches (19.7 ft). Alta Guard Station has a 100-year snowpack height of 204 inches, with a maximum observed height of 218 inches. Assuming the starting zones above Alta have 15% deeper snowpack than Alta Guard Station, provides an estimated 100-year design snowpack height of 235 inches (19.5 ft) in the starting zones. This does not account for wind transported snow, which will occur in parts of all of the paths. On a 35-degree slope, a snowpack depth of 235 inches translates to a snowpack depth (measured perpendicular to the surface) of 193 inches (16 ft), which is close to the largest size flexible nets currently available and used internationally, which are 16.4 ft (D_k=5.0 m).

This demonstrates that permanent snow nets may not be feasible for some or all of the starting zones above Alta both in terms of availability of suitable flexible structures, or prohibitive costs for rigid structures.

It should also be noted that mono-anchor structures (e.g. Vela nets) are not be considered suitable for this terrain, given the deep snowpack height, large loads on structures and the limited height currently available commercially, that is less than the design snowpack height in the starting zones, even exclusive of potential wind-loading of snow.

Table 8 provides a summary of the areas of starting zones, average slope angle, design snow depth and resulting cost estimate for snow support structures in the starting zones.

Table 8. Snow supporting structure cost estimates for avalanche paths affecting the TOA.

Path	Area (Ha)	Area (Acre)	Average Slope Angle	Snow depth (ft)	Est. Cost based on $2.5M/Ha
Cardiff	4.4	10.9	40	15.0	$11 Million
Toledo	15.0	37.2	38	15.5	$38 Million
Flagstaff Low	1.7	4.1	33	16.4	$4.2 Million
Flagstaff	7.2	17.8	36	15.8	$18 Million
Binx	3.3	8.3	34	16.3	$8.4 Million
Flagstaff Mine	0.7	1.7	37	15.6	$1.7 Million
Emma 1	6.1	15.1	33	16.5	$15 Million
Emma 2	3.8	9.5	33	16.4	$9.6 Million
Emma 3	3.7	9.1	33	16.3	$9.2 Million
Emma 4	2.3	5.6	34	16.1	$5.6 Million
Culps West	0.9	2.2	37	15.7	$2.3 Million
Culps	2.9	7.1	35	16.1	$7.2 Million
Davenport Left	0.6	1.4	37	15.7	$1.4 Million
Davenport	1.7	4.3	34	16.3	$4.3 Million
Total	**54**	**134**			**$135 Million**

From Table 8, it is very apparent that the cost of snow supporting structures in Alta could only be considered for relatively small, specific starting zones that would provide protection for high value structures in the runout zone. Unless one of these specific areas can be identified within the project area, snow supporting structures are not a recommended option.

5.1.2 Snow Sheds

Snow sheds are rigid, concrete and/or steel structures that protect a road by diverting avalanches overtop of the structure (Figure 13). Snow sheds mostly eliminate avalanche to a road, except in cases where they are not sufficiently long and can have the portals overtopped.

F&P (2006) considered snow shed options for the White Pine area of Mid-Canyon, and presented a thorough evaluation of potential costs based on work by Lochner (2006). Snow

Figure 13. Two-lane concrete Lanark snow shed in Rogers Pass, British Columbia. A. Jones photo.

sheds that were 1235' and 2485' long were estimated to cost $29.5 Million for a 1235' long shed at White Pine Chutes 1-4, and $58.7 Million for a 2485' shed at White Pine Chutes 1-4, White Pine and Little Pine. Estimates were for 2-lane sheds.

The construction cost of a concrete snow shed was estimated by Lochner (2006) to be $10,496/linear foot in year 2010 for two lanes. This was based on historical costs from sheds constructed in other areas. Using a CPI Inflation calculator, that can be assumed to be $11,500/linear foot in 2016 (10% increase from 2010).

The avalanche paths above the TOA present an almost continuous avalanche hazard area to SR-210, which is a continuous distance of approximately 4700' from the western edge of Cardiff to the eastern edge of the Davenport/Grizzly path. Conceptually, a continuous snowshed through this entire length would cost on the order of $55 Million, but this would present a number of significant issues:

- The western portal at the Cardiff path overlaps with hazard areas from Hellgate near the Alta Bypass Road, which may increase the risk in this area.
- A snow shed will increase the runout distance and frequency of avalanches reaching areas within the TOA below the road, which will significantly increase risk to structures and people below the road. Also, the current road serves as a catchment for avalanche deposits, which can be removed following avalanche control.
- There are numerous businesses and access points that would become inaccessible from the current roadway (e.g. Goldminers Daughter Lodge, Snowpine Lodge, Lodge Road, residences). Alternate access in the valley bottom would be required.
- Removes access to significant amounts of parking areas along the roadway.
- Still requires the use of artillery Overfire (or other protective measures such as RACS) to protect buildings and individuals in the TOA.
- Essentially transfers risk from people in vehicles to structures and people in the TOA.

<u>For these reasons, a continuous snowshed through the TOA avalanche hazard area is not considered feasible and is not recommended.</u>

Shorter shed sections could be considered, as shown in Table 9 and Figure 14. These sheds would join the main avalanche hazard areas with breaks in the relative ‘safe zone’s, which are only lower frequency areas rather than hazard free. This could include a 1000' shed through Cardiff and Toledo, an 1150' shed through the Flagstaff Low-Flagstaff-Flagstaff Mine paths, and a 1750' shed through the Emma 1-5-Culps-Davenport/Grizzly paths. These concepts are very preliminary and would need to be evaluated to determine the length of shed based on detailed evaluation of avalanche path characteristics and historical records. Typically snow sheds are constructed sufficiently long to protect against 30-year design dense flow avalanches.

Shorter shed sections could mitigate some of the TOA access issues discussed above, but would still present the same problem of increased avalanche runout and frequency (and thus risk) to structures located downslope of the snow shed. This also makes future development within the TOA more difficult due to the increased avalanche risk. It also presents significant roadway engineering challenges for UDOT and the TOA, which would need to be considered in addition to the shed costs.

For the reasons discussed above, in addition to the high costs ($10-20 Million per shed), sheds are not considered a feasible or recommended option for the avalanche paths in the study area.

Table 9. Cost estimate for snow shed options.

Paths Covered	Length (ft)	Estimated Cost in 2016
Cardiff-Toledo	1000	$11.5 Million
Flagstaff Low, Flagstaff, Flagstaff Mine	1150	$13.2 Million
Emma 1-5, Culps, Davenport, Grizzly	1750	$20.1 Million
Combined: Cardiff – Davenport/Grizzly	4700	$54 Million

*Based on an estimated unit cost of $11,500/linear ft for a 2-lane shed.

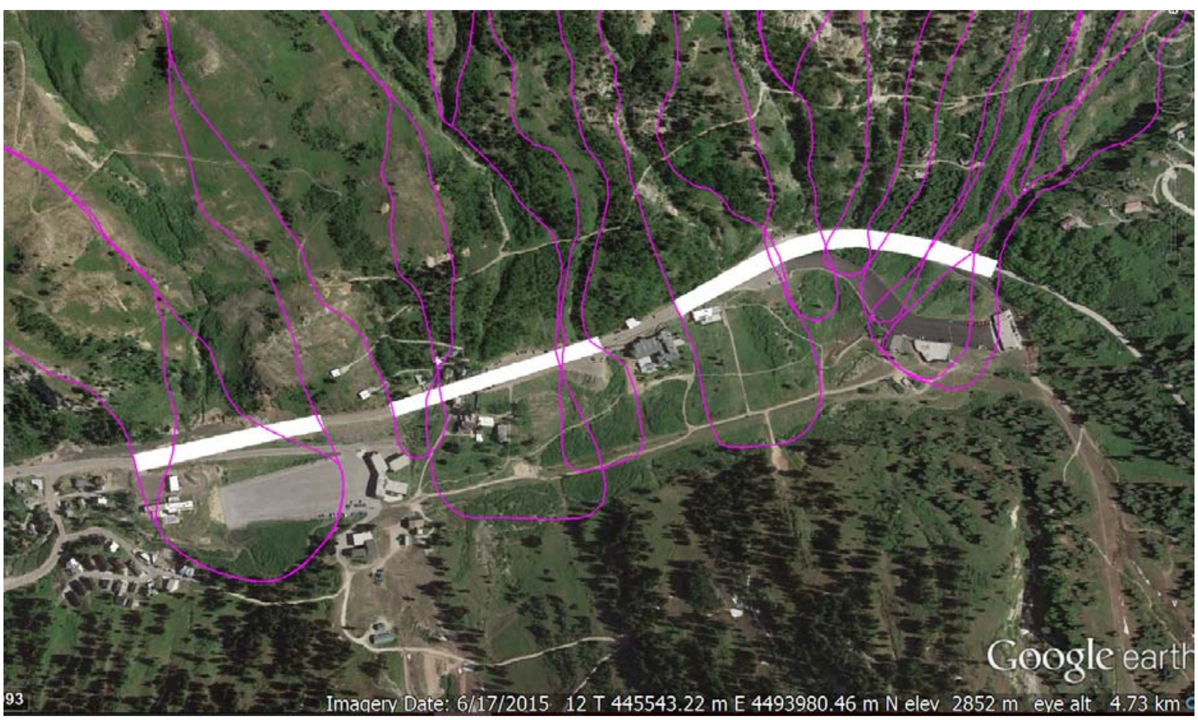


Figure 14. Snow shed options (white polygons) within the TOA avalanche path section. Includes Cardiff-Toledo (left), Flagstaff Low-Flagstaff Mine (middle) and Emma 1-Davenport/Grizzly (right). A continuous snow shed would simply join all three structures shown.

5.1.3 Earth Berms (Stopping Dams and Diversions)

Earth berms are large, earthfill structures that are constructed in the runout zone to divert or stop avalanche flow. Berms that stop avalanches are called *stopping dams*, berms that divert flow are called *diversion berms*. Berms are typically constructed of compacted earth, but other materials such as geotextiles and facing units (e.g. gabbions, concrete blocks, stacked rock) can be used to create a steep upslope face and reduce the amount of fill needed. The “China Wall” at the base of the White Pine path is an example of an earthfill berm with stone facing.

Two earthfill berms were observed in the TOA project area, one in the Emma 5 (Culps West) (Figure 15) and the other in front of the Peruvian Lodge (Figure 16). The Emma 5 berm was constructed to protect a residence located on the eastern edge of the path; it is approximately 150' long by 10-15' high. The Peruvian Lodge earthfill berm was constructed in the parking area to protect parts of the Peruvian Lodge, which was impacted by avalanches from the Toledo path in 1997 and 2002. The berm is approximately 100' long by 55' wide, and an estimated 15' high.

Figure 15. Earthfill berm in Emma 5 (Culps West) to protect residence.

Figure 16. Earthfill berm (highlighted in red, with arrow) in front of the Peruvian Lodge.

Figure 17. Stacked rock diversion wall in Emma 1 path, near TOA water reservoir.

A stacked and mortared rock wall diversion structure is present in the Emma 1 path near the TOA water reservoir access (Figure 17). This wall is approximately 220' long and typically 5-7' high (average approximately 6'). This wall was assumed to be constructed to keep avalanches flowing to the east in the gully, but avalanches were observed to have continued straight from this point directly to the Snowpine Lodge. Due to the limited height of this wall (it is often buried in the winter); this wall will be ineffective at diverting most avalanches in the Emma 1 path.

Berms need to be constructed sufficiently high to either stop avalanche flow or divert it. The height is determined by the sum of: height of snow on the ground; height of previous deposits; the avalanche flow height; and, most importantly, the speed of the avalanche which determines the run-up height of the avalanche on the berm. Avalanches will run up higher on a stopping dam where the dam is oriented perpendicular to the flow compared to a diversion berm, where the berm is oriented obliquely to the flow direction. The closer the berm orientation is to parallel the avalanche flow direction, the lower the run-up height that occurs.

At Alta, the nature of the terrain (e.g. typically gullied and/or with smooth ground cover) and often dry snow characteristics results in very fast moving, turbulent mixed-flow avalanches, which have a basal dense flow component and a turbulent powder component. Wet flows are also common in the spring and also need to be accounted for in design of berms. Because of the fast moving avalanches, diversion and stopping berms need to be very high to be effective for the dense flow, and are typically ineffective for stopping or diverting the powder component.

Avalanche modelling was completed for paths in the study area, which provided design avalanche velocities typically in the range of 30-40 m/s (98-131 ft/s), averaging 35 m/s (115 ft/s). Faster velocities are possible in the larger paths like Toledo and Flagstaff (e.g. 50 m/s, 164 ft/s), which would need to be determined on a path by path basis.

For a stopping dam, an avalanche moving at 35 m/s (115 ft/s) would have a runup height on a stopping dam (oriented perpendicular to flow) of approximately 135 ft. A diversion berm oriented at 30 degrees to the flow direction would have a runup height of approximately 50 ft. These numbers do not consider snow on the ground, previous deposits or flow heights, and illustrate the height required to permanently mitigate avalanche hazard to the road or TOA using berms.

From the runup analyses, it is apparent that fully stopping avalanches in these paths is unlikely, so any structure considered should have a lower height that would aim to reduce the frequency of avalanches reaching the road to an acceptable level, rather than stop them. Occasional avalanche control would still be needed with any berm option in this area.

Lochner (2006) presented potential berm options and associated costs for the White Pine (650') and Little Pine (600') avalanche paths. Berm structures were evaluated that were 36' high, which was based on an expected avalanche velocity of 15 m/s (50 ft/s). This would reduce the return period of avalanches reaching the road, but not stop all avalanches. Berms were assumed to be as long as the avalanche path is wide, and constructed with earth with a 1.5 horizontal to 1.0 vertical slope (34 degrees). Based on a combined berm length of 1,250 ft and a cost estimate (2005) of $5,105,500, that works out to a unit cost of $4,084/linear foot of 36' high berm. Projecting that unit cost to 2016 is approximately $5,000/linear foot. Based on the berm embankment volumes assumed in Lochner (2006), the costs can also be expressed as approximately $47 per cubic yard of embankment volume (includes excavation, placement, compaction) in 2016 dollars.

Table 10 presents a very conceptual estimate of stopping/diversion berms that could reduce the frequency of avalanches reaching the road, as well as reduce risk to structures within the TOA. The approximate locations of these structure concepts are shown in Figure 18.

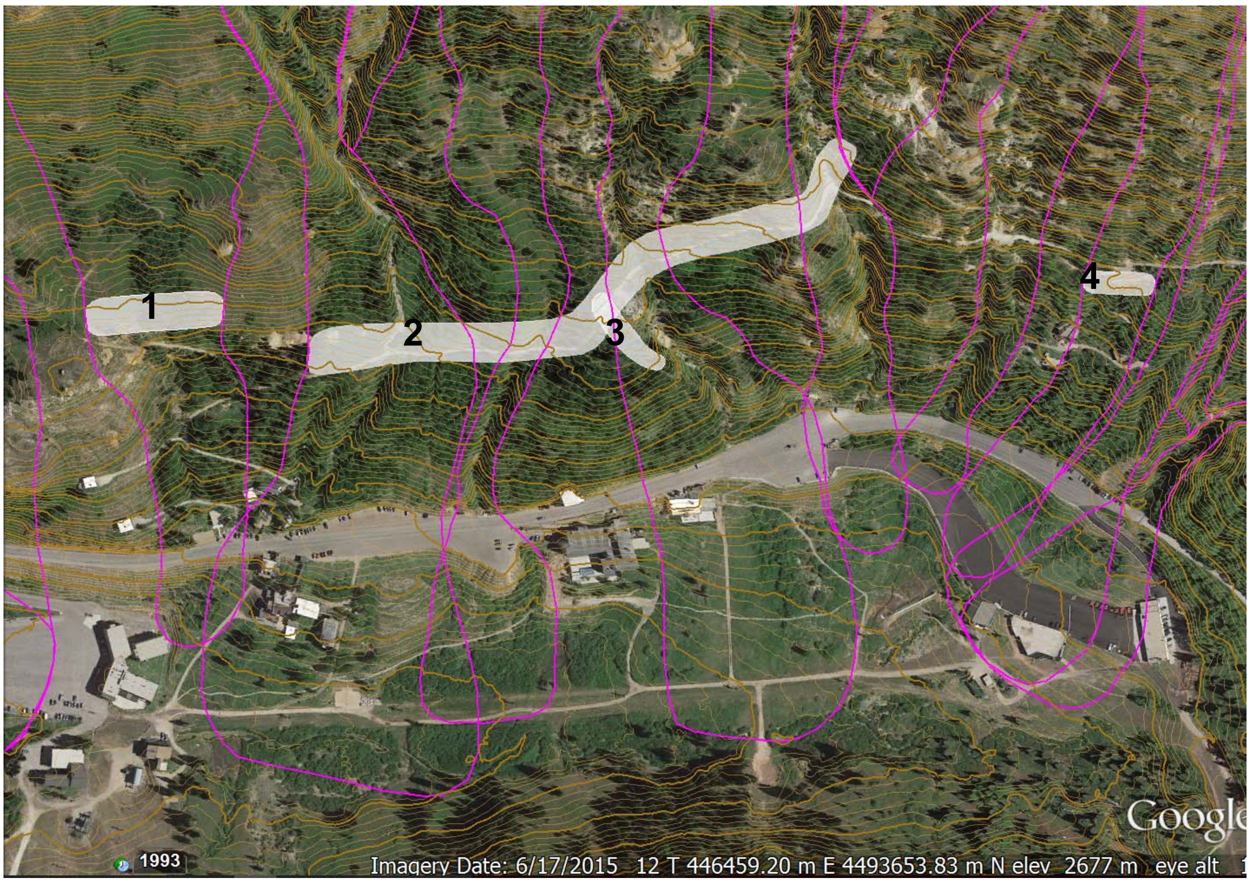


Figure 18. Conceptual earth fill diversion/stopping dam locations. 1 = Flagstaff Low; 2 = Flagstaff to Emma 2/3; 3=Emma 1 diversion to east; 4=Emma 5 (Culps West).

The lengths correspond to the width of the path where a berm could be constructed, the height is assumed to be 36' (unless noted), and the unit cost is assumed to be $5000/linear ft. These numbers are intended to give very rough, conceptual lengths and costs for discussion purposes; each site would need a detailed review to evaluate feasibility and site specific requirements.

There are many considerations that would need to be considered with earth fill berms, including:

- Environmental impacts due to excavation and moving of earth, including impacts to water resources in the Salt Lake City watershed.
- Visual (aesthetic) impacts to the landscape. These would be large structures that would require a long time to revegetate, if they could even be revegetated.
- Disturbance of potentially contaminated mining waste materials.
- Impacts to recreational uses, particularly skier traffic.

- Expected continuing need for future avalanche control (e.g. artillery, helicopter bombing), albeit at a much reduced frequency of control.
- Will not be effective for very fast moving design avalanches, and will be overtopped by powder avalanches.
- Diversions will divert avalanche flow to adjacent areas, which may reduce the hazard in one path and increase it in the other. This may have legal implications in some areas, particularly for private land holdings.

Earth berms are often a very effective means of avalanche hazard mitigation; however, at this location they are expected to have limited reduction in avalanche hazard as well as a relatively high cost. For this reason, as well as the considerations provided above, <u>earth fill berms are not currently recommended for the project area, or considered further in this report.</u>

Table 10. Cost estimates for conceptual earth fill diversion/stopping berm options.

Path(s)	Length (ft)	Cost ($)	Comments
Cardiff / Toledo	Not estimated	Not estimated	● Diversion/stopping dam not feasible above road due to high speed, turbulent & confined flow in gully ● Option to improve diversion berm in front of Peruvian, but this is below the SR-210. Currently 100 long by ~15' high, would need significant height & length increase to be effective against design avalanches. ● Berm improvement may reduce risk to Peruvian from dense flow, but may increase risk to structures to the west or to the Wildcat parking area to the east. ● Berm would provide negligible reduction of powder avalanche risk to Peruvian.
Flagstaff Low	450	$2,250,000	● Stopping dam could be constructed on bench east of old gun tower, between 8825' and 8950' ● Not recommended due to high height and cost, and limited impact to road with control program (T>25 yrs) ● Height could be reduced by having a series of large benches and smaller dams (i.e. check dams). ● Increased risk to adjacent paths (Toledo, Flagstaff) of avalanches flowing around berm, powder will overtop.
Flagstaff	530	$2,650,000	● 530' long stopping dam could be constructed along existing road bench and above near 8800' ● Very high runup, smaller (e.g. ~36' high) structure could reduce return period of dense flow to road ● Avalanche control would still be needed for larger, overtopping events, when berm is full, and for powder. ● Berm could end up diverting flow towards Flagstaff Low.
Flagstaff Mine	130	$650,000	● Path only infrequently reaches road and it is not currently controlled, so structure is not warranted. ● Structure needed with extended berm so that flow diverted from Emma 1 doesn't channel down Flag. Mine.
Emma 1 (Diversion to West)	230	$1,150,000	●Emma 1 stopping dam could be constructed on existing road bench near 8900' ● Would need to be diverted to the east in conjunction with Emma 2/3 and Flagstaff diversion so that flow is not just diverted to an adjacent path.
Emma 1 (Diversion to East)	315	$788,000	● Larger diversion berm would parallel existing rock wall, in approximately same location. ● Assumed diversion is 18' high since berm is 20 degrees from flow direction, lower runup height. ● Assumed 50% construction cost ($2500/linear ft) due to half height structure. ● Diversion would reduce risk to Snowpine Lodge by channeling flow into gully and parking areas to the east. ● No change in risk to the highway since avalanches just diverted and reach highway with similar frequency.
Emma 2/3	310	$1,550,000	● Avalanche flow is diverted out of Emma 2/3 gully westwards into diversion/stopping dam. ● Potential for flow to continue west towards Emma 1 gully, so potentially needs a continuous berm structure.
Flagstaff to Emma 2/3 (Continuous)	1975	$9,875,000	● Continuous (or near continuous) stopping dam/diversion berm, assumed 36' high for footprint. Extends from Emma 2/3 to Flagstaff on existing road bench and on mostly relatively gentle terrain. ● Detailed investigation would likely allow structure to be broken up into smaller lengths, but full length assumed for general concept.
Emma 4	n/a	n/a	● Avalanche track is too steep and confined for a diversion/stopping berm option.
Emma 5 (Culps West)	240	$600,000	● Structure could be built off of existing diversion berm near 8960' elevation. ● Current structure diverts flow to the west, construction of full width of path could stop flow, but would need to increase from current ~15' to approx. 30-36'. Assume $2500/linear ft for already partially built structure. ● Would protect residences, but since the path is not currently controlled and does not typically affect the highway, there is no net benefit to the UDOT program. This would strictly be a benefit to residential areas.
Culps	n/a	n/a	● Avalanche track is too steep and confined for a diversion/stopping berm option.
Davenport	n/a		● Avalanche track is too steep and confined for a diversion/stopping berm option.

5.1.4 Stopping Walls

Stopping walls are constructed to stop avalanche the dense flow components of avalanche, usually in the runout zone and adjacent to a highway or structure that is to be protected. Stopping walls can be constructed of a variety of materials and by various methods, including:

- Reinforced concrete
- Concrete blocks (e.g. Lock-blocks)
- Gabbion basket/wire mesh
- Soldier Piles (e.g. driven piles with wood cross members)
- Snow fence/catcher

Examples of various types of stopping walls are shown in Figure 19.


Reinforced concrete wall


Concrete block wall (Lock-blocks)


Gabbion basket/wire mesh wall.


Snow fence/catcher barrier


Soldier Pile wall (H-Piles and timbers)

Figure 19. Examples of stopping walls.

Stopping walls are typically constructed where there are space restrictions, otherwise earth fill diversions or stopping dams tend to be more economical and can be constructed much higher. They are generally ineffective at mitigating very turbulent avalanches and powder avalanches.

The SR-210 roadway in the TOA was reviewed to determine areas where stopping walls may be feasible. There were no locations identified where stopping walls would be effective. All of the paths reviewed produce fast moving, turbulent avalanches that would simply overtop these structures, and explosive avalanche control would still be needed to reduce risk to acceptable levels.

However, there may be locations below the SR-210 within the TOA where stopping walls could be considered for protection of structures, particularly high value residential or commercial structures. Potential effectiveness of these structures would need to be evaluated by owners of the buildings, but could also be considered for future construction if additional valley bottom development is considered in the future.

5.2 Active Control Options

5.2.1 Artillery

The UDOT avalanche program in LCC uses artillery as the primary tool for avalanche control in the paths above the TOA (Figure 20). Sections 2.2, 4.3, 4.4 and 4.5 provide discussion of the current artillery program, including issues associated with the use of artillery control above occupied buildings. To summarize, the main issues currently associated with artillery use above the TOA include:

- *Overhead Fire*, where artillery projectiles are fired over occupied buildings.
- *Shrapnel* from detonation of projectiles, which typically have a safe standoff distance of 3000'; occupied buildings are within this distance and there is potential to impact a backcountry skier in a closed area.
- *Overshoots*, potential to overshoot a ridge and impact an unintended target, either due to operator error or projectile/weapon malfunction.
- US Army withdrawing artillery or temporarily/permanently shutting down usage; this could occur in the event of an accident either at Alta or any other avalanche control program using artillery in the US.
- *Ammunition supply*, the US Army may restrict access to Howitzer ammunition for reasons beyond UDOT's control.

<u>It is in UDOT's interest to reduce their dependence on the use of military artillery above the TOA</u> for the reasons listed above, and seek either permanent mitigation solutions, or other alternative active control options.

Figure 20. 105 mm Howitzer artillery at the P-Ridge gun tower.

Figure 21. Hand charging.

5.2.2 Hand Charging

Hand charging involves the deployment of small explosive charges by avalanche control personnel directly into avalanche starting zones (Figure 21). This method is used in areas where the avalanche starting zones can be readily accessed by workers on skis or foot, and is the primary avalanche control method used by most North American ski areas. Hand charging is typically not relied upon by highway avalanche safety programs due to the limited access to starting zones, and need to have highway personnel at the highway level to manage risk.

ASL completed a study of alternate avalanche control methods for avalanche paths above the TOA that looked at using hand charging on south facing slopes between Flagstaff and Culps (ASL, 2009). This review was conducted with consideration of a proposed chairlift installed along the Flagstaff Shoulder, which separates the Flagstaff and Toledo paths.

The following conclusions were provided by ASL (2009):

- It was determined that the area between Flagstaff and Culps (Targets P75 to P91) could be safely controlled by deployment of hand charges under most conditions.

- There would be times when some targets located on lower slopes below the ridge could not be safely accessed or controlled by hand.
- Control by hand charging would normally be as effective as artillery control, except during times when workers could not safely access the targets lower on the slope, which can reliably be controlled by artillery under any weather or avalanche conditions.
- Control of the ridge from Flagstaff would require a team of 8 workers (3 teams of 2 workers, plus an emergency back-up or rescue team of 2).
- An avalauncher may be required to control targets in Toledo Bowl, Toledo Face, Toledo Chute and Cardiff Bowl.

The program described above is essentially the level of work that would be needed to operate an avalanche safety program for a ski area, except that it would be conducted by workers who also have additional responsibilities within the remainder of the highway avalanche areas in LCC. It might also be used in the event that the US Army suspends the use of military artillery by non-military organizations in response to an incident or accident.

The use of hand charging for control of avalanches above the highway and TOA cannot be considered sufficiently reliable and is not recommended. Even if a chairlift were installed on Flagstaff Shoulder, alternate means of control (e.g. RACS) would be recommended to protect the highway and TOA during times that chairlift access was not possible (e.g. at night, during major wind storms, mechanical failures, etc.) or when avalanche/weather conditions prevented access to targets located below the ridge.

Transference of responsibility for public safety from a governmental agency to a private ski area is typically not standard practice, but there are precedents in the US. For example, the Alpine Meadows avalanche safety team is responsible for monitoring and controlling avalanche paths on the Alpine Meadows Road, under contract to Placer County, CA. These paths affect both the county road as well as residential areas, and present similar issues to those faced by the TOA.

5.2.3 Skier Compaction / Ski Cutting

Figure 22. Skier compaction (Source: UDOT).

Skier compaction involves the stabilization of the snowpack by repeated skiing, which reduces the potential for avalanche formation (Figure 22). Repeated skiing compacts and work-hardens the snow, and disturbs weak layers such as surface hoar and facets. Ski cutting is similar in that it involves an avalanche professional intentionally triggering small avalanches by skiing through a start zone under controlled conditions and with appropriate safety precautions. Skier compaction and ski cutting are relied upon by ski area avalanche safety programs, but are not normally used for protection of highway areas threatened by avalanche hazards.

Skier compaction is relevant to the TOA avalanche study due to a chairlift that has been proposed to transport skiers to the top of Flagstaff via the Flagstaff Shoulder. This would essentially turn most of the south facing terrain above the TOA into a controlled, downhill ski area. Currently, there is repeated backcountry skier traffic in this area, but with insufficient traffic to be considered effective skier compaction.

Skier compaction is typically an effective method for control short-term (storm) instabilities in the snowpack, but has limited effect on deeply buried, persistent weaknesses. These weaknesses typically are responsible for the larger (D3) avalanches that can reach the SR-210. Skier compaction can reduce the frequency at which avalanches affect the road, but does not remove the hazard from the more dangerous, larger avalanches that may affect SR-210.

A single chairlift to the top of Flagstaff Shoulder would only reach part of the terrain that needs control above SR-210; additional lifts would likely be needed to effectively cover the entire ridge with skier compaction. Installation of lifts in this area would also limit the use of artillery, which can damage lifts.

Although skier compaction combined with hand charging would result in a limited reduction in avalanche hazard to the SR-210 and TOA, these methods would not be sufficiently reliable to reduce the hazard to an acceptable level, given the high traffic volumes, concentrations of public within the TOA, and numerous occupied structures for the same reasons discussed in Section 6.2.3 above.

5.2.4 Helicopter Control

5.2.4.1 Helicopter Control Using Explosives

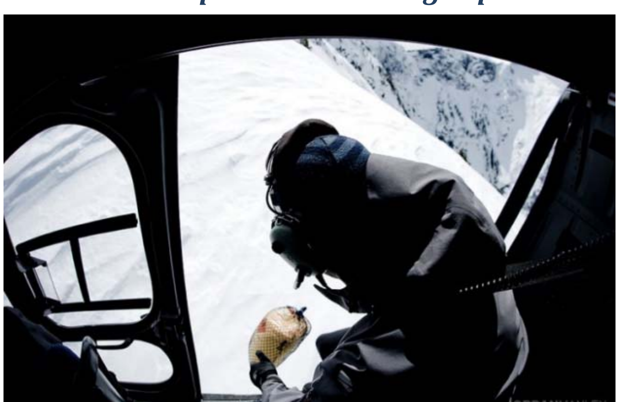


Figure 23. Helicopter control. Photo: J. Manley.

Helicopter control involves the deployment of explosive hand charges from a helicopter directly into avalanche start zones (Figure 23). This technique is used by avalanche safety programs throughout North America, and is considered a standard method, especially for highway programs where start zones are inaccessible. UDOT infrequently uses helicopter control in some of their start zones.

Although helicopter control is a reliable method for controlling avalanches in some areas, it cannot be used during storm periods when helicopters are unable to operate due to wind and/or snowfall, and can only be conducted during daylight hours. This contrasts to artillery and RACS that can be used day or night, and under any weather or avalanche conditions.

Helicopter control methods should be continued to be used by UDOT as needed, and could be used to supplement the RACS program described later in this report. There are a number of targets where installation of RACS are not warranted, because they are in close proximity to other targets with RACS, they are targets that are infrequently controlled by artillery, or they are in paths that only infrequently affect the road (e.g. Grizzly). Helicopter control can reliably be used to control these infrequent targets and supplement a RACS or artillery program, removing additional targets from the Overhead Fire trajectories.

Figure 24. Daisy Bell. Photo: J. Bozon, TAS.

5.2.4.2 Helicopter Control Using Daisy Bell

Daisy Bell is a mobile RACS device that is carried below a helicopter on a long line and detonated above a start zone (Figure 24). Daisy Bell creates an explosion using a mix of oxygen and hydrogen, and is very similar to the O'BellX, both of which are supplied by TAS/MND. UDOT recently purchased a Daisy Bell for use in LCC, both for controlling areas between RACS and for controlling cornices.

Daisy Bell can only be used during suitable periods for flying a helicopter, and cannot be used at night, during most storm periods and during periods of strong winds. The times when Daisy Bell can be used are essentially the same as when helicopter control methods can be used, but there is a larger capital investment required with Daisy Bell. This system is particularly useful for control of areas with many starting zones located within a small area, as the recharge time of the system is quick and the avalanche technician is not limited by waiting for confirmation of detonation using the timed safety fuses with conventional explosives used in helicopter control.

The choice of whether to use a Daisy Bell or helicopter control (or both) is a matter of operational efficiency as determined by the avalanche control team and helicopter pilots. Some operations find they improve the efficiency of their program, others prefer helicopter control.

For the TOA paths, either the new Daisy Bell or helicopter control could be used to supplement the RACS network, and to replace low frequency targets that result in Overhead Fire.

5.2.5 Remote Avalanche Control Systems (RACS)

Remote Avalanche Control Systems (RACS) are explosive devices that are permanently installed in an avalanche start zone and are detonated from a remote location to trigger an avalanche. Currently available systems either detonate a mixture of gasses (Gazex and O'BellX) or a conventional explosive charge (Wyssen Tower, Avalanche Guard/Master).

UDOT already has an extensive network of Gazex and several O'BellX systems and is in the process of procuring and installing additional systems. All of the currently available systems are reviewed in this report, although it's understood that UDOT already has a large infrastructure and training investment in TAS products (Gazex and O'BellX), and is likely to continue to develop this network in the future. Thus, additional detail provided in this report emphasizes

Gazex systems. This should not necessarily preclude the consideration of alternate RACS, which may be better suited to specific locations, or offer capital cost advantages.

5.2.5.1 Gazex (TAS, France)

Gazex do not use explosives, but rather detonate a mixture of propane and oxygen gasses in a galvanized steel cylinder by means of electronic initiation. There are over 2300 Gazex exploders installed worldwide, some of which have been in operation for over 25 years.

Gazex exploders are available in three standard sizes: 0.8 m^3, 1.5 m^3 and 3 m^3, which represents the volume of gas detonated by the system. The exploder size is chosen according to the configuration of the avalanche terrain, and required area of effect. Larger units produce a larger explosion and have a greater area of effect, but also use more gas.

Gazex can either have the gas stored in a chest next to the exploder (autonomous), or connected by a pipe to a central gas shelter capable of storing sufficient gas reserves for the entire season for multiple exploders. Shelters should ideally be located in areas of snow scour, or raised above the expected snow depth to ensure year-round access. Gas lines may be laid on the surface between the shelter and the exploder, or they can be buried to prevent damage from rockfall, wildlife and the public. Helicopters are is used by most operations to deliver recharged gas cylinders to the shelters.

In addition to the three standard sizes, there are three models available with differing costs and installation costs/benefits: Fixed Exploder, Inertia Exploder, and Gazflex Exploder.

The Gazex Fixed Exploder is the original design, but is generally no longer recommended for new installations. It is fully anchored to the ground both at the base and at the end of the exploder; this produces relatively high ground forces and anchoring requirements, which increases the maintenance requirements.

Figure 25. 1.5 m^3 Gazex installation at Loveland Pass, Colorado. Photo: A.Jones.

Due to the anchoring and maintenance issues described above, most new installations are now completed using the Gazex Inertia Exploder system (Figure 25). This system works similar to the Fixed Exploder, but is articulated at the base and rests on a mobile counterweight system that absorbs the upwards forces from the blast. This system is better for locations with sub-optimal anchor conditions, and has lower maintenance requirements than the older fixed system.

The Gazflex Exploder system is supported by a flexible bar anchored to the ground, which dissipates forces and transfers them to the anchor. This reduces the cost of installing extensive foundations, and is particularly useful for steep, rocky locations with difficult access.

Because conventional explosives are not used by this system (but rather gases), transportation, storage and security issues related to conventional explosives are not relevant. This greatly simplifies the permitting process in some jurisdictions.

Gazex systems require a large amount of infrastructure to be installed relative to other RACS, including larger foundations, pipelines and gas shelters. Thus, Gazex also has a relatively high maintenance requirement and potentially higher installation costs compared to other systems. However, this may be balanced by the relatively lower consumable costs.

Gazex are widely used in the USA and Canada, including Teton Pass (Wyoming DOT), Colorado DOT, CalTrans, Nevada DOT, Kootenay Pass (British Columbia Ministry of Transportation and Infrastructure), and Parks Canada (Banff National Park).

The Gazex system is recommended for consideration by UDOT for the paths above the TOA, and is thus evaluated in detail in Section 6 of this report.

5.2.5.2 O'BellX (TAS, France)

O'BellX systems, like Gazex, do not use explosives, but rather detonate a mixture of gases (hydrogen and oxygen, Figure 26). O'BellX is self-contained and does not require a separate shelter for gas storage or installation or pipes. It is easier to install than Gazex, with simpler anchoring requirements and smaller foundations. However, the size of the denotation is substantially smaller, potentially requiring additional units to cover the same area controlled by a comparable Gazex system. The blast of an O'BellX is approximately comparable to a 0.8 m^3 Gazex unit, but improvements are being made to make it similar to a 1.5 m^3 unit. Up to 30 shots may be fired without reloading gas.

The O'BellX operational module is removed by helicopter to carry out maintenance and refilling in the valley bottom during the summer, also reducing the visual impacts if stored at the base.

Figure 26. O'BellX installation in Chamonix, France. A. Jones photo.

O'BellX installations in the US include Wyoming (WYDOT) and one operated by UDOT in LCC. There are currently no O'BellX installations in Canada, but numerous installations in Europe.

Costs are provided in Section 6 for O'BellX systems; however, given the higher costs and lower radius of effect compared to the Gazex system, O'BellX should only be considered for specific locations, such as where autonomous units with small starting zones may be considered (e.g. Toledo Chute and Culps Low).

5.2.5.3 Wyssen Tower (Wyssen Avalanche Control, Switzerland)

Wyssen Tower is a secure explosive storage system that is placed adjacent to the start zone and loaded with pre-armed explosives. The system holds 12 charges, which are up to 10 lbs. The deployment box is installed on a tower, which overhangs the avalanche starting zone (Figure 27).

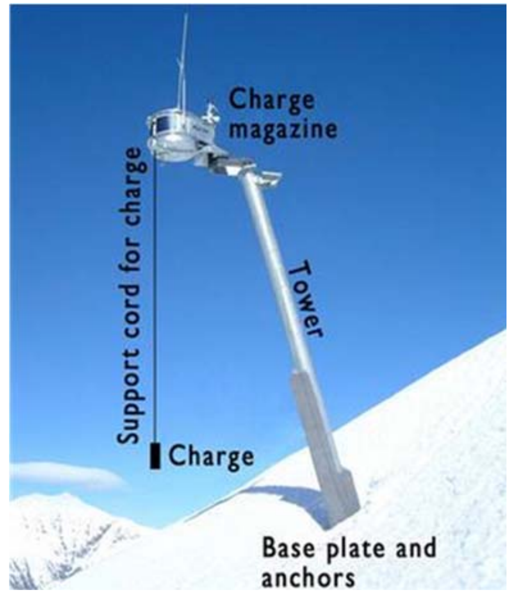


Figure 27. Wyssen Tower installation in Switzerland. Photo source: Wyssen.

A coded radio signal initiates the detonation process in the deployment box. The charge is dropped from the deployment box on a cord, which holds the explosive charge in place above the snow surface. As the charge is dropped, two safety fuse assemblies are ignited by a percussion lighter (mechanical lighter), and detonation occurs after a delay, as determined by the fuse length (12 inches). The height of the tower can be adjusted for each site, so that the charge is placed at an optimal height above the snowpack.

The entire deployment box is removed from the tower by helicopter for reloading, and can be recharged during the winter with up to 12 charges (e.g. up to 24 charges with a mid-winter recharge). Comparable to the O'BellX system, the deployment box can be stored in the valley bottom during the summer, but the visual impact of the tower remains year-round.

One of the advantages of the Wyssen Tower over other comparable systems (e.g. Gazex, Avalanche Guard) is the large radius of effect of up to 425 ft, which is effective upslope and laterally from the tower. This is achieved by the air blast effect of up to a 10 lb explosive, which is greater than the blast radius of other systems which are directed downwards into the snowpack, and downslope. This greater radius of effect means that potentially fewer units can be installed in some areas; for example, a single Wyssen Tower can sometimes be installed on a ridge between two targets and effectively control both starting zones.

Wyssen Tower can offer an advantage in terrain where the installation and maintenance of a Gazex would be complicated or present a risk to workers. Wyssen Towers have small, relatively simple foundations (approx. 1 cu. yd.). While O'BellX could also be considered in these difficult locations, Wyssen Tower offers a significantly stronger blast with a larger radius of effect than O'BellX, potentially resulting in the need for fewer installations.

As a result of the relatively small and simple foundation, the installation cost of a Wyssen Tower may be less than that of a Gazex unit in complicated and hazardous terrain.

Cost estimates are provided in this report for Wyssen Tower systems at target locations proposed for Gazex, but no detailed evaluation of tower placements are provided. The number of Wyssen Towers was reduced to 17 in consideration of some placement optimizations. This allows for cost comparisons by UDOT for equivalent RACS products. There may be the opportunity to optimize the design and reduce the number of installations with Wyssen Tower due to the larger radius of effect.

Wyssen Towers have not yet been approved for use by a US regulator, but they have been approved for use in Canada and are being installed in two locations in British Columbia. Some jurisdictions have concerns with the storage of pre-armed explosives in remote, mountain areas, but those issues have been overcome in comparably strictly regulated European jurisdictions (e.g. Switzerland, Austria, Norway) and in Canada.

Wyssen Tower could be considered for selected sites in place of a Gazex or O'BellX where the terrain presents challenging installation, a larger radius of effect is desirable, or where overall lesser amounts of installed infrastructure is preferred.

5.2.5.4 Avalanche Guard/Avalanche Master (Inauen Schatti/CIL, Switzerland)

The Avalanche guard system is similar in concept to the Wyssen Tower, with pre-armed explosives contained in a secure deployment box (Figure 28). A typical installation has two deployment boxes, each oriented to launch explosive charges at separate targets. Each box can be loaded with 10 charges (up to 8.8 lbs).

Figure 28. An Avalanche Guard installation in Wyoming. Photo: J. Hendrikx.

The explosive charge is launched from the box via radio communication from a computer operated by authorized personnel at a remote location. Instructions are received at the site and the specified explosive charge is launched. Two safety fuse assemblies are ignited by a mechanical igniter as the charge is propelled out of the magazine by an electronically detonated base charge. The explosive charge reaches its target and detonates after the lit safety fuse assembly detonates the blasting cap.

The Avalanche Master uses similar mechanics to the Avalanche Guard, except that the charge is simply lobbed into the starting zone while tethered with a cord, comparable to the Wyssen Tower system. The remainder of the process and system components are similar to the Avalanche Guard.

The Avalanche Guard system has been accepted in at least one other US jurisdiction (WYDOT, Wyoming), but is not currently in use in Utah. There is also one system used in Colorado, but it has not been approved for remote use. Avalanche Guard has also been approved and is installed by the BC MoTI in Canada for highway protection, and Parks Canada recently installed 8 Avalanche Guard units in Rogers Pass.

Similar to Wyssen Tower, cost estimates are provided for Avalanche Guard systems for the equivalent targets proposed to be controlled by Gazex. There are some substantial cost savings with Avalanche Guard compared to other systems since two boxes can be installed on the same tower, sharing foundation and communications systems. Additionally, pre-cast concrete slabs can be used for the foundation, which does not require ground disturbance by drilling anchors.

One disadvantage to the Avalanche Guard/Master is that reloading must be done at the installation location, which can be challenging during mid-season. It is also limited by 10 charges, which would be insufficient in many of the TOA target areas in a typical winter, but especially so in a heavy snow winter.

Given UDOT's current investment in TAS products (Gazex and O'BellX) and gas RACS, there is likely not a compelling reason for UDOT to change to an Avalanche Guard RACS network for the avalanche paths above the TOA. Thus, Avalanche Guard is not recommended as a RACS to replace the artillery targets above the TOA.

5.2.6 Explosive Trams

The CATEX system (**CA**ble for **T**ransporting **EX**plosives) is an engineered, automated explosive delivery system, similar in ways to the commonly used bomb tram system. Many ski resorts in the USA and Canada have built and operate simple explosive trams systems for avalanche control. These are usually constructed with a cable and bull wheel system, and explosives are delivered to starting zones either manually or with a hand-crank wheel. They provide a simple, effective explosive air blast into an avalanche starting zone, which is more effective than a blast in the snowpack. There are currently no CATEX systems installed in the US or Canada, but they are used extensively in Europe.

Figure 29. CATEX aerial tramway base station in Saint Francois Longchamp ski resort, France. A. Jones photo.

CATEX consists of a wire cable that is suspended by a series of towers, which spans over selected avalanche starting zones. An explosive charge is attached to the cable with a clamp, which is then advanced to a pre-selected location above an avalanche starting zone using a drive station. The cable can be moved forwards and backwards to allow for delivery of an explosive charge to an optimal location (Figure 29).

Several options exist for CATEX, including an automated, electric motor drive system or a manual (hand-crank) version. Manual versions are only useful for short distances. Power can be supplied to the automated systems by a conventional electric line, or by a battery system.

Conventional explosive charges are detonated either with a safety fuse assembly (i.e. time delay detonation) or by remote electronic detonation. Charges can be attached to the cable with a rope extension that places the charge above the snowpack, or by using a mechanical lowering device that places the charge above the snowpack.

The cable is supported using conventional lift towers but, due to the relatively low loads, towers comparable to a ground-based lift system (e.g. rope tow, platter) can be used. Towers typically require installation of a concrete foundation, which significantly increases the cost of the system.

Like a lift system, CATEX are subject to icing issues on the cable and sheaves. This can be overcome with regular cycling of the cable which produces vibrations and reduces riming/icing. There are also greater visual impacts with a CATEX system when compared to the Gazex due to the towers and cable.

Although the CATEX system could be effective for the south facing terrain above TOA, the large amount of ridgeline infrastructure and impacts to ridgeline views will likely not be an option for this project area. Additionally, there are some critical targets located a distance below the ridgeline that could not be controlled by a single CATEX system. For these reasons, CATEX is not recommended and not discussed in detail in this report.

5.2.7 Avalanche Detection Systems

UDOT installed an Infrasonic Avalanche Detection system in 2006 to monitor three locations in LCC: White Pine, White Pine Chutes and Little Pine. F&P (2009) presented the results of an evaluation of preliminary results of this system in the Infrasound Avalanche Monitoring System Research Evaluation (F&P, 2009). The results, based on discussions with UDOT operations personnel, found that the Infrasound system achieves its objectives, specifically that: Infrasound system provides reliable warning of the onset of natural avalanche cycles, reliably confirms control results, and increases public and worker safety. This system has become an indispensable part of the UDOT avalanche forecasting program in LCC.

There are also cost efficiencies and reduced closure times that result from the use of this system, although amounts remain difficult to quantify.

UDOT is currently working on expansion of their avalanche detection system program in key areas, notably the Snowbird, Superior and Hellgate areas, in addition to the TOA area. Unfortunately, the current Infrasound system is unique and cannot readily be replaced or expanded to other areas due to software comparability issues with currently available hardware. The company which supplied the current system and software are no longer offering a turn-key product, so UDOT needs to look into other suppliers.

A positive result of this challenge is that UDOT is currently sourcing out alternative technologies that may provide comparable or improved avalanche detection, either using infrasound technology, radar or a combination of technologies. This field of science is rapidly evolving and there are excellent systems already in use for avalanche detection in Europe. Other transportation groups in the US and Canada are interested in the development and implementation of avalanche detection technologies. For example, an infrasound system provided by Wyssen Avalanche Control is currently being installed by Parks Canada in Rogers Pass to evaluate the system for this upcoming winter.

Although specific costs for avalanche detection systems are not currently available, UDOT is currently sourcing out a radar system with equipment, software and programming costs on the order of $100,000. Radar systems have been developed and applied with success to avalanche hazard areas in Europe; these systems should also be considered as an alternative or compliment to infrasound.

It is strongly recommended that UDOT continue to develop and expand their avalanche detection network, particularly within the paths that affect the TOA. These systems will further reduce risk to people on the road and in the TOA, and further reduce closure numbers and times.

6.0 Evaluation and Costing of options

Section 5 presented active and control and structural (passive) mitigation options for consideration for the avalanche paths above the TOA. The optimal system will serve to replace the current artillery program in these paths and reduce or eliminate the need for Overhead Fire, as well as reduce avalanche hazard to the SR-210, structures and people in the TOA. This section summarizes options by path and provides recommendations for the preferred option(s).

Table 11 presents a summary of the key pros and cons for each of the options considered, as well as recommendations. Evaluation of the systems is made based on a combination of the following factors:

- Capital cost
- Installation cost
- Operation & Maintenance cost
- Effectiveness (area of effect, air vs. snow blast)
- Reliability
- Proven technology with many installations (ideally in North America and Utah)
- Foundation requirements
- Visual impacts (aesthetics and landscape impacts)
- Environmental impacts
- Permitting/regulatory requirements
- Security (explosives, gasses)
- Personnel safety (especially with respect to explosives vs. gases, and winter access)
- Redundancy
- Simplicity of use

As much as possible, Table 11 tries to capture the main pros/cons associated with each option so each factor can be weighed according to UDOT's priorities. A few of these factors are considered critical for this location, in particular: permitting/regulatory requirements; visual impacts; security; and effectiveness. Table 12 summarizes active control options by path.

The permitting/regulatory requirement is critical; without approval of local regulators a given system cannot be installed. The two systems where this is considered critical is the Wyssen Tower and Avalanche Guard/Master systems. Although these are both reliable, effective options, they currently they have not been accepted for use in Utah, and have the associated issue of placing a pre-armed explosive deployment box in the starting zone. These security issues have been overcome in many other jurisdictions, but for some jurisdictions this may present a critical stopping point for these two systems.

The CATEX may be subject to a similar permitting/regulatory issue but for another reason. In the case of the CATEX, conventional explosives are used, but these are detonated from a cable at a location remote to where the blaster is (i.e. well outside of the blast zone). This is also the case with the Gazex and O'BellX systems (i.e. the blast occurs at a location remote from where the blaster is), but those systems do not use explosives and are not regulated as explosive devices. Thus, the same explosive regulations would not apply to the Gazex and O'BellX as would apply to the CATEX, which uses conventional explosives. Although this may present a challenging issue to overcome for UDOT, this issue can be overcome since it is not dissimilar to launching artillery and avalauncher rounds into a starting zone from a remote location, which are both accepted control methods at LCC.

Both the Gazex (Inertia) and O'BellX systems have many excellent pros for an installation in LCC. They do not have any of the explosive permitting/regulatory issues associated with other systems, and most importantly Gazex is a proven, permitted system in the US and Utah. They are also reliable, proven systems with installations throughout the world.

O'BellX system has substantially higher capital costs when compared to a comparable Gazex, and the range of effect is not as good. For comparison, a 1.5 m^3 Gazex Inertia with a Chest would be approximately $64K, while a comparable O'BellX unit would cost approximately $150K. However, the O'BellX has lower installation costs and improved worker safety for maintenance, which for some sites may balance out the overall cost and effectiveness of the system.

There is also the concern the mixing of various systems in the LCC, and issues with system compatibility and shared maintenance costs. UDOT already has a large infrastructure investment in the TAS products (Gazex and O'BellX), so there should be a compelling reason to bring a completely different system into the mix, unless these products cannot achieve the same objectives, or are of a much higher cost. One such reason may be in terrain that presents difficult installation and maintenance of Gazex, or unacceptable risk to workers needing to access a site on foot/ski. In such a location, a Wyssen Tower could be considered.

The following sections present preliminary cost estimates for the RACS in the avalanche paths above the TOA. These estimates are based on information provided by the suppliers, and based on the authors' experience with other installations.

Table 11a. Summary table with key pros and cons of the considered passive control options.

System	Pros	Cons
Passive control		
Snow Nets	• Mostly an install and forget solution (permanent mitigation of hazard). • Limited ongoing maintenance (annual inspection, periodic tensioning and debris removal). • Long term passive mitigation. • Permanently mitigates risk to both the road and residential areas below. • Re-zoning of residential areas below may be possible with permanent mitigation.	▪ Very high materials and installation costs. ▪ High uncertainty with cost due to limited number of large scale installations in North America. ▪ High visual (aesthetic) impacts. ▪ High recreation impacts (interferes with ski touring activities). ▪ Maximum available height may not be sufficient for starting zones, with consideration of wind-loading. ▪
Snow Sheds	• Long term passive mitigation. • Permanently mitigates risk to the road. • Limited ongoing maintenance (annual inspection / structural checks).	▪ Very high materials and installation costs. ▪ High visual (aesthetic) impacts. ▪ Does not reduce Overhead Fire since protection of TOA will still be required. ▪ Transfers the risk to downslope infrastructure and property residential areas below. ▪ Will reduce some of the parking alongside the road and access to businesses. ▪
Earth Berms	• Long term passive mitigation. • Permanently mitigates risk to the road and some residential areas. • Limited ongoing maintenance (annual inspection / structural checks). • Relatively cheap for structural mitigation (when compared to nets / or snow sheds). • Re-zoning of residential areas below may be possible with permanent mitigation.	▪ Environmental impacts due to excavation and moving of earth, including impacts to water resources in the Salt Lake City watershed. ▪ Visual (aesthetic) impacts to the landscape. ▪ Disturbance of potentially contaminated mining waste materials. ▪ Impacts to recreation (interferes with ski touring activities). ▪ Continuing need for avalanche control, albeit at a reduced frequency. ▪ Will not be effective for very fast moving design avalanches. ▪ Berms will divert avalanche flow to adjacent area, reducing hazard in one path and potentially increasing it in another. ▪
Stopping Walls	• Long term passive mitigation for specific events. • Permanently mitigates risk to the road and some residential areas. • Limited ongoing maintenance (annual inspection / structural checks). • Relatively cheap for structural mitigation (when compared to nets / or snow sheds). • Some re-zoning of residential areas below may be possible with permanent mitigation.	▪ High materials and installation costs for only a limited range of avalanche types / sizes. ▪ All of the paths affecting the road in this study produce fast moving, turbulent avalanches that would simply overtop any reasonable stopping wall structures. ▪ Visual (aesthetic) impacts to the landscape. ▪ Impacts to recreation (interferes with ski touring activities). ▪ Continuing need for avalanche control with Overhead Fire, albeit at a reduced frequency. ▪

Table 11b. Summary table with key pros and cons of the considered active control options.

System	Pros	Cons
	Active control	
Gazex (Inertia)	• Range of size and model options to adapt to different terrain and foundation conditions. • Provides large detonation, effective range up to 300 ft. • Uses gas mixture instead of explosives (i.e. no transport, storage or use of explosives). • Gas supply sufficient for full season of use without recharging, even in major winters. • Widely used, proven technology. • Approved by regulators for use in Utah. • Up to 10 exploders can be connected to a single shelter (but typically up to 5 or 6). • Simultaneous detonation of multiple exploders possible.	▪ High capital cost. ▪ High installation cost due to foundations (excavation, drilling, forming, concrete pour). ▪ Relatively large size, visual impacts (reduced by grey color, below ridge). ▪ Surface gas lines can be damaged by animals, rockfall, landslides, avalanches (most will be buried at TOA installations). ▪ Large amount of infrastructure (exploders, foundations, pipelines, shelters) results in the highest maintenance requirement of all RACS. ▪ Fixed location, difficult to adjust or move once installed. ▪ Can stabilize snowpack around the exploder, reducing effectiveness. ▪ Any winter maintenance/repairs needs to be completed at the site.
O'BellX	▪ Lower installation costs (relative to Gazex) due to simpler anchoring. ▪ No gas lines (fully self-contained). ▪ Uses gas mixture instead of explosives (i.e. no transport, storage or use of explosives). ▪ Main unit can be removed during summer, reducing visual impacts. ▪ Unit can be removed during the winter and reloaded/serviced at the base, if required. ▪ Simultaneous detonation of multiple exploders possible. ▪ Due to simpler anchor requirements, re-location (at a cost) is feasible.	▪ High capital cost. ▪ Smaller detonation than Gazex, approx. equivalent to the smallest (0.8 m^3) Gazex. ▪ One model / one size. ▪ Fixed location (but easier to move than Gazex). ▪ Limited installations in North America. ▪ Relatively new technology. ▪ Can stabilize snowpack around the exploder, reducing effectiveness. ▪ Low gas supply compared to Gazex (UDOT is working with TAS on a system with a larger gas supply).
CATEX	▪ Multiple targets (paths and individual locations) controlled from one site. ▪ Can adjust target locations for variable conditions (wind, snowfall). ▪ Provides air blast, explosive can be lowered above snowpack. ▪ Explosive size can be varied depending on target and snowpack. ▪ Electronic trigger option available. ▪ Simultaneous detonation with electronic triggers an option. ▪ Low cost of conventional explosives. ▪ Large area of effect due to air blast (~ up to 450 ft for a comparable charge to Wyssen).	▪ High capital cost. ▪ High installation cost (many towers with foundations). ▪ High visual impacts with towers and cable across ski areas. ▪ Increased personnel and closure time on mission days. ▪ Icing of the cable, sheaves, and other components. ▪ Many mechanical parts require inspection and maintenance. ▪ Transport of explosives to site and field assembly of explosives. ▪ Duds are possible, require retrieval and disposal. ▪ Fixed location, very costly to modify. ▪ Maintenance involves putting personnel onto towers.
Wyssen Tower	▪ Large area of effect (up to 450 ft) due to air blast ▪ Blasting height over snowpack can be varied. ▪ Deployment box is retrieved by helicopter, can be reloaded and serviced mid-winter. ▪ Deployment box can be stored during summer. ▪ Charges on retained on cord, cannot slide. ▪ Low cost of conventional explosives (e.g. can accommodate conventional emulsion charges) ▪ Simultaneous detonation of multiple exploders possible. ▪	▪ Explosives security. ▪ Regulatory issues to be address with respect to storing pre-armed explosives. ▪ Duds are possible, require retrieval and detonation. • Potentially visual impacts with tower on ridgeline • Only holds 12 charges, which may be insufficient for some TOA targets, or require mid-winter re-charging.
Avalanche Guard	• Two targets can be controlled from one tower site. • Relatively small foundation required since blast does not occur at base. • Pre-cast concrete slab foundation does not require excavation, drilling, or forming concrete.	▪ Explosives security. ▪ Door can freeze open or shut (riming). ▪ High cost of explosive charges, non-standardized cast booster. ▪ Many moving parts, some operations have reliability issues. ▪ Only holds 10 charges per target, which may be insufficient for some TOA targets, or require mid-winter re-charging. ▪ Access to site required for reloading. ▪ Regulatory issues to be address with respect to storing pre-armed explosives. ▪ Duds are possible, require retrieval and detonation. ▪ Charges can slide (solved for Avalanche Master with charge on a cord). ▪ Variability with target precision due to many variables (e.g. base charge amount, charge fit, wind). ▪ Detonation takes place in snowpack (smallest radius of effect of all RACS).

Table 12. Summary of RACS options by avalanche path.

Path	Target Number	Target Name	Gazex	O'BellX	Wyssen Tower	Avalanche Guard
Toledo Bowl	57	Toledo Chute Low	-	-	-	-
	59	Toledo Chute	1 x 1.5 m^3 (Auto)	1	1	1
	61	Toledo Face	2 x 3.0 m^3	2	1 (controls both Gazex targets)	2
	63	Toledo Bowl	-	-	-	-
	65	Toledo Bowl High	1 x 3.0 m^3	1	1	1
	67	Toldeo Bowl Right	1 x 3.0 m^3	1	1	1
Flagstaff Low	69	Flagstaff Low	1 x 3.0 m^3	1	1	1
Flagstaff	70	Flagstaff Shoulder Low	-	-	-	-
	71	Flagstaff Shoulder	1 x 3.0 m^3	1	1	1
	73	Flagstaff Gut	-	-	-	-
	75	Flagstaff High	1 x 3.0 m^3	1	1 (common to target 75 & 77)	1
	77	Flagstaff High Right	1 x 3.0 m^3	1		1
	78	Flagstaff Low Right	-	-	-	-
Binx's Folly	79	Binx's Folly	1 x 3.0 m^3	1	1	1
Emma 1 Left	80	Emma 1 Left	1 x 1.5 m^3	1	1	1
Emma 1	81	Emma 1	1 x 3.0 m^3	1	1	1
	83	Emma 1 Right	1 x 1.5 m3	1	1	1
	84	Emma 1 Right Low	-	-	-	-
Emma 2	85	Emma 2	1 x 3.0 m^3	1	1	1
Emma 2 Right	86	Emma 2 Right	1 x 1.5 m^3	1	1	1
Emma 3	88	Emma 3 Left	1 x 3.0 m^3	1	1 (common to target 87 & 88)	1
	87	Emma 3	1 x 1.5 m3	1		1
	90	Emma 3 Right	-	-	-	-
Emma 4	89	Emma 4	1 x 3.0 m^3	1	1	1
Culps	91	Culps	1 x 3.0 m^3	1	1	1
	92	Culps Low	1 x 1.5 m^3 (Auto)	1	1	1
TOTAL	**26 Targets**		**14 x 3.0 m^3 4 x 1.5 m^3 2 x 1.5 m^3 (Auto)**	**20**	**17**	**20**

6.1 Gazex (Inertia) Cost Estimate

Table 13 provides estimated capital and installation cost for an Inertia Gazex system in the paths above the TOA, excluding Cardiff which is being evaluated separately by UDOT. This includes installations in Toledo through Culps, which includes 20 exploders.

Equipment costs are based on information provided by suppliers in 2015, with a 5% contingency to account for potential increases in the next 1-2 years.

Installation costs are estimated based on similar settings, where installation costs are typically 1.5 to 2.0 times the equipment capital cost. Given UDOT's extensive experience with installation of Gazex, the lower 1.5 multiplier was assumed as the mid-cost. Installation costs can fluctuate by approximately ± 25%, so a range of costs are provided: low (-25%), mid and high (+25%). Costs are lower if installations are done in-house, so it may be reasonable for UDOT to assume the lower cost estimate for this project, assuming some in-house personnel construction.

UDOT (Matt McKee, pers. comm.) suggested that recent UDOT Gazex installations have tended to be costed at approximately $200K per unit installed, which is comparable to typical industry costs. The estimates presented below are conservative, and consider potential installation by an independent contractor.

The estimated cost for installation of 20 Gazex Inertia exploders with 5 standard shelters and 2 mini-shelters (for autonomous units) ranges from $3.5 Million to $4.7 Million, plus an estimated $30,500 in annual operation and maintenance. The mid-range of this estimate is $4.1 Million, which is approximately $175,800 to $236,600 (mid-cost estimate of $202,800) per exploder, installed. This is consistent with the $200K unit cost noted by UDOT.

The annual opeartion and maintenance cost estimate of $30,500 represents approximately 1% of the capital cost, which considers annual maintanance but also period replacement and/or upgrading of components over a typical design life of 20-30 years. Jay Bristow from MND recommended a service package for the Gazex system for a minimum period of 2 years, which would include one maintenance field visit in the spring ($5,000) after completion of winter operations, and a second in the fall, prior to winter start-up ($5,000). Maintenance requirements for the Gazex are minimal in the first few years, but periodic part upgrades/replacement should be anticipated as the system ages.

The material supply costs are reasonably accurate values based on thousands of installations around the world. The main variables in installation costs have to do with anchor and foundation conditions, site access, and competitiveness of bids received from contractors. Observations of access and rock quality conditions indicate that these aspects could be expected to keep costs in the low to mid-range of this estimate. Availability of qualified contractors and the resulting bid prices would be expected to provide the most uncertainty in the cost estimates provided.

Appendix A – Gazex System Option shows the recommended locations of Inertia Gazex units. The 5 proposed shelters are located on gentle terrain that would be accessible along the ridge under most avalnche conditions. This avoids having to put personnel within avalanche terrain for inspection or changing of the gas supplies at the shelters.

The two autonomous units (Flagstaff Low and Culps Low) are located lower within the avalanche paths and are thus potentially exposed to overhead avalnche hazard. Re-supply of these mini-shelters, if needed during winter, would need to be done during low hazard periods.

Table 13. Estimated capital, installation and O&M costs for a 20 unit Gazex RACS system.

Location (Number)	Size	Exploder	Splitter	Shelter	Shelter type
Toledo Chute	1.5 m^3	$37,800		$26,250	Autonomous with mini-shelter
Toldedo Face	3.0 m^3	$48,300		$52,500	Toledo Shelter (2 Gazex)
Toledo Face	3.0 m^3	$48,300			Toledo Shelter (2 Gazex)
Toledo Bowl High	3.0 m^3	$48,300		$52,500	Flagstaff Shelter (5 Gazex)
Toldeo Bowl Right	3.0 m^3	$48,300			Flagstaff Shelter (5 Gazex)
Flagstaff High	3.0 m^3	$48,300	$6,000		Flagstaff Shelter (5 Gazex)
Flagstaff Shoulder	3.0 m^3	$48,300			Flagstaff Shelter (5 Gazex)
Flagstaff Low	3.0 m^3	$48,300			Flagstaff Shelter (5 Gazex)
Flagstaff High Right	3.0 m^3	$48,300	$6,000	$52,500	Binx Shelter (4 Gazex)
Binx's Folly	3.0 m^3	$48,300			Binx Shelter (4 Gazex)
Emma 1 Left	1.5 m^3	$37,800			Binx Shelter (4 Gazex)
Emma 1	3.0 m^3	$48,300	$6,000		Binx Shelter (4 Gazex)
Emma 1 Right	1.5 m^3	$37,800		$52,500	Emma 2 Shelter (3 Gazex)
Emma 2	3.0 m^3	$48,300	$6,000		Emma 2 Shelter (3 Gazex)
Emma 2 Right	1.5 m^3	$36,000			Emma 2 Shelter (3 Gazex)
Emma 3 Left	3.0 m^3	$48,300	$6,000	$52,500	Emma 4 Shelter (4 Gazex)
Emma 3 Right	1.5 m^3	$37,800			Emma 4 Shelter (4 Gazex)
Emma 4	3.0 m^3	$48,300			Emma 4 Shelter (4 Gazex)
Culps	3.0 m^3	$48,300			Emma 4 Shelter (4 Gazex)
Culps Low	1.5 m^3	$37,800	$6,000	$26,250	Autonomous with mini-shelter
TOTALS					
Exploders (20)		$901,200			
Shelters (7)		$315,000			
Splitters (6)		$36,000			
Freight (6)		$100,000			
Materials Sub-Total		**$1,352,200**		Average material cost = $67,610/unit	
Installation (low)		$2,163,500			
Installation (mid)		**$2,704,400**		Average installation cost = $135,220/unit	
Installation (high)		$3,380,500			
Total cost (low)		$3,515,700		Low installed cost = $175,800/unit	
Total cost (mid)		**$4,056,600**		**Mid installed cost = $202,800/unit**	
Total cost (high)		$4,732,700		High installed cost = $236,600/unit	
Annual Maintenance		$13,334		Assume $667/unit/year (based on $6000/9 units)	
Consumables, Helicopter		$17,200		Assume $500/unit/yr gas/parts/supplies + 4 hrs helicopter @$1800/hr	
Annual Cost		**$30,500**			

These locations are central to the control targets used by UDOT. Supplemental control using helicopter control may occassionally be needed near some of the targets, but overall these exploders would control the majority of avalanche hazards affecting the paths above the TOA.

One area that did not receive a RACS in this study is Davenport. The return period of this path to the road (~20 years) and infrequent artillery control (total of 3 rounds during 2003-2012) show that this path can be effectively managed using occasional helicopter control with explosives or Daisy Bell, or by continued occasional use of artillery, accepting the overfire issue.

6.2 O'BellX Cost Estimate

For comparative purposes, Table 14 provides the estimated cost of installation of O'BellX at each of the same target locations shown in Table 13. A total of 20 O'BellX units would be needed for this installation. Because O'BellX units are autonomous, shelters are not needed, but splitting structures are included at 6 locations to protect the system from avalanche impacts. This is an unlikely installation because of the smaller size and radius of effect of the O'BellX compared to Gazex, but this estimate is provided for comparative purposes; the optimal solution would be expected to include Gazex only, or a combination of Gazex with O'BellX at some sites.

Each O'BellX costs approximately $150,000 (J. Bristow, pers. comm.), plus an estimated $100,000 per foundation anchor based on recent tenders for RACS in Canada. Installation costs are substantially less than Gazex because O'BellX require only 4 anchor bolts, limited ground preparation and limited concrete work, and no pipelines. However, installation costs provided encompass the full suite of potential costs, including geotechnical engineering, helicopter costs, etc. The material cost for O'BellX is higher than Gazex, and thus the total cost is higher, $5.1 Million for the mid estimate compared to $4.1 Million for the Gazex mid cost estimate. O&M are assumed to be the same as Gazex ($30,500/yr for 20 RACS).

Table 14. Estimated capital, installation and O&M costs for a 20 unit O'BellX system.

Item	Units	Cost ($)	Total	Comment
O'BellX	20	$150,000	$3,000,000	Estimate from MND in 2015
Splitters	6	$6,000	$36,000	
Freight (container)	4	$20,000	$80,000	
Sum Materials			**$3,116,000**	Average material cost = $155,800/unit
Installation (low)			$1,600,000	-
Installation (mid)			**$2,000,000**	Average installation cost = $100,000
Installation (high)			$2,500,000	
Total cost (low)			$4,716,000	Low installed cost = $235,800/unit
Total cost (mid)			**$5,116,000**	Mid installed cost = $255,800/unit
Total cost (high)			$5,616,000	High installed cost = $280,300/unit
Annual Maintenance			$13,334	Assume $667/unit/year (based on $6000/9 units)
Consumables, Helicopter			$17,200	Assume $500/unit/yr gas/parts/supplies + 4 hrs helicopter @$1800/hr
Total Annual Cost			**$30,500**	

The main disadvantage of the O'BellX compared to Gazex is the lower effective radius. A wider radius of effect will be needed for many of the targets, which are best controlled using the larger 3.0 m^3 Gazex exploders. There may be potential to install O'BellX at some locations, but for this report we've assumed either a complete Gazex or O'BellX system.

6.3 Wyssen Tower Cost Estimate

Wyssen Tower RACS have a larger radius of effect compared to other RACS because they detonate up to a 10 lbs (5 kg) suspended explosive charge, which produces an air blast with an effective radius of up to approximately 425 ft with the right terrain conditions. The avalanche paths were reviewed with consideration of this wider radius, which resulted in 17 Wyssen Towers instead of 20 units. The two Toledo Face targets were combined, Flagstaff High and Flagstaff High Right were combined, as were Emma 3 Left and Emma 3 Right. Table 15 provides the estimated cost of installation for 17 Wyssen Towers.

Because the Wyssen Tower exploder is installed on a mast approximately 26' above the snowpack (or higher as dictated by the terrain and snowpack), it is less vulnerable to impacts by avalanches, so splitting structures were not accounted for in this estimate. Some towers that are subject to large avalanches or cornice fall may require reinforcement or splitters.

Table 15. Estimated capital, installation and O&M costs for a 17 unit Wyssen Tower system.

Item	Units	Cost ($)	Total	Comment
Wyssen Tower	17	$115,000	$1,955,000	Estimate from Wyssen in 2016.
Splitters	0	$0	$0	
Freight (container)		$0	$0	Included in tower unit price
Sum Materials			**$1,955,000**	Average material cost = $115,000/unit
Installation (low)			$1,360,000	-
Installation (mid)			**$1,700,000**	Average installation cost = $100,000/unit
Installation (high)			$2,125,000	
Total cost (low)			$3,315,000	Low installed cost = $145,600/unit
Total cost (mid)			**$3,655,000**	Mid installed cost = $169,000/unit
Total cost (high)			$4,080,000	High installed cost = $199,500/unit
Total Annual Cost (Maintenance, consumables)			**$61,200**	Assume $300/charge all in, including explosives (12 per exploder), maintenance, helicopter time.

The Wyssen Tower system presents a similar capital costs compared to the Gazex system, with a mid-cost estimate of $3.7 Million for 17 RACS. However, the annual operation cost of $61,200 is expected to be more than 2 times higher than Gazex or O'BellX, due to the higher cost of custom explosive charges compared to gas.

6.4 Avalanche Guard Cost Estimate

An Avalanche Guard system could be installed at gently sloping or flat locations along the ridgeline and launch explosives into the starting zone. Each tower can hold two boxes which launch at different targets. Based on a preliminary review of targets, approximately 11 towers with 20 boxes would be required to reach all of the targets of interest. Table 16 provides the estimated cost of installation of the Avalanche Guard system.

Based on the results of a recent project in Rogers Pass, each unit is assumed to have a materials cost of $136,150, with installation cost of $104,500.

Table 16. Estimated capital, installation and O&M costs for a 11 Avalanche Guard Systems (11 towers with 20 boxes).

Item	Units	Cost ($)	Total	Comment
Avalanche Guard	20	$136,150	$2,723,000	Estimate from Rogers Pass in 2016.
Splitters	0	$0	$0	
Freight (container)		$0	$0	Included in tower unit price
Sum Materials			**$2,723,000**	Average material cost = $136,000/unit
Installation (low)			$846,200	
Installation (mid)			**$1,100,000**	Average installation cost = $100,000/unit
Installation (high)			$1,430,000	
Total cost (low)			$3,569,200	Low installed cost = $178,500/unit
Total cost (mid)			**$3,823,000**	Mid installed cost = $191,150/unit
Total cost (high)			$4,153,000	High installed cost = $207,650 /unit
Total Annual Cost (Maintenance, consumables)			**$70,000**	Assume $350/charge all in, including explosives (10 per exploder), maintenance, helicopter time.

The Avalanche Guard system also presents similar capital costs compared to the Gazex and Wyssen Tower systems, with a mid-cost estimate of $3.8 Million for 20 RACS. However, the annual operation cost of $70,000 is expected to be more than 2 times higher than Gazex or O'BellX, due to the higher cost of custom explosive charges compared to gas.

6.5 Splitters to Protect Against Overhead Hazard

Some of the proposed RACS locations are below the ridge and may be subjected to avalanche impacts from above. These locations were reviewed and two measures could be implemented to reduce this hazard, as discussed below.

The Gazex system is robust and designed to withstand impacts from some (but not all) avalanches. For RACS locations that could be impacted by avalanches from above, potential impact pressures could be evaluated and, if neeeded, a splitting wedge could be installed to divert flow and reduce impact forces (Figure 21). The splitter would be installed just upslope of the exploder and anchored with four GEWI rods.

The approximate cost of this structure supplied by TAS is $5,500-6,000, but a simliar system could also be manufactured locally, possibly at lower cost.

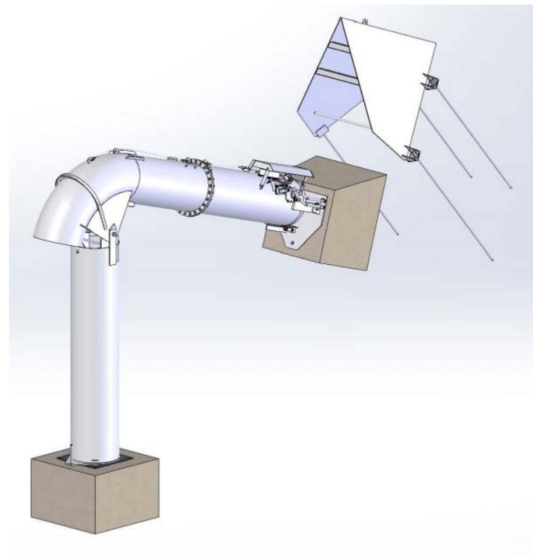


Figure 21. Splitting wedge for Gazex exploder (Source: TAS).

It is important to emphasize that detailed ground truthing will be required for any locations to determine the optimal exploder location and whether splitting wedge protection should be considered.

6.6 Construction

With most installations, construction costs are the largest unknown in the provision of the estimated costs. Installation was based on similar settings, where installation costs are typically 1.5 to 2 times the equipment cost. However, this cost can fluctuate by approximately ±25% depending on the site specifics, time of year and access. Generally, costs are lower if installation is done in-house, but this also internalizes any delays and potential installation setbacks. The cost estimates provided in the previous sections include consideration of this ±25% range. Because of UDOT's history of Gazex installations and knowledgeable, local contractors, it is anticipated that the costs would come in at the lower end of this cost scale.

For the snow net option, there is a high uncertainty in cost estimates due to the limited number of large scale snow net installation projects in North America. Installation costs are typically 3-4 times the materials cost for snow nets due to the site preparation (e.g. scaling) and drilling required, plus the helicopter time.

Helicopters would be needed for any of the RACS installations above the TOA. This will include transport of materials for foundations (forms, rebar, concrete, grout, water), lifting equipment into place (drill rig, compressor, RACS components), and (for some areas) personnel transport. Helicopter costs during construction are included in the estimates provided above.

A geotechnical assessment will be needed to determine the anchoring/foundation requirements for both RACS systems. Rock scaling may be needed prior to construction at some sites for worker protection.

6.7 Supply of equipment

Parts for RACS systems are designed and manufactured in Europe. These will need to be transported to the site via shipping containers; long delivery times should be anticipated (e.g. > 6 weeks or greater). Any potential spare parts (extras, breakage, defective parts) should be ordered at the same time as the main order.

Gas supplies for the Gazex systems are provided by standard gas supply companies. Typically a full winter supply is flown into the site in the fall and recharge is not needed during the winter. Extra bottles can be added to the array if seasonal use typically exceeds the initially installed tank farm.

Snow nets are also, for the most part manufactured in Europe and shipped in containers to the site. Some supplemental or modified parts (e.g. shackles, cables) may be supplied or manufactured locally if needed.

7.0 Recommendations

The intent of this study is to provide UDOT, the TOA, and ASL a definitive, clear direction to meet the objectives of reducing the avalanche hazard while reducing or eliminating the practice of firing artillery over the TOA. Based on our field observations, historical data analysis, and discussions with UDOT avalanche forecasters, the following recommendations are provided:

- Passive control measures are not currently recommended for the TOA study area. All present significant challenges including high cost, feasibility due to great design snowpack depths and high avalanche velocities, consideration for downslope infrastructure, private land, aesthetics and impact to the environment and recreation.
- RACS are recommended to replace artillery targets that require Overhead Fire. Gazex is recommended for consideration by UDOT for the paths above the TOA.
- Wyssen Towers could be considered for select sites in place of a Gazex or O'BellX where the terrain presents challenging installation or larger radius of effect is needed.
- Helicopter control could be used to supplement the RACS, (e.g. low frequency targets) using either a Daisy Bell or conventional explosive deployment.
- It is strongly recommended that UDOT continue to develop and expand their avalanche detection network, particularly within the paths that affect the TOA. This could include expansion of the Infrasound system, potentially complimented by radar technology, which is becoming increasingly used in Europe for avalanche hazard applications.

Three RACS were recommended for consideration: Gazex, O'BellX and Wyssen Tower. A cost summary for each of these systems is presented below.

Item	Gazex		O'BellX		Wyssen Tower	
	Item Sub Total	*Unit Cost*	Item Sub Total	*Unit Cost*	Item Sub Total	*Unit Cost*
Materials Cost	$1,352,200	*$67,610*	$3,116,000	*$155,800*	$1,955,000	*$115,000*
Installation Cost (low)	$2,163,520	*$108,176*	$1,600,000	*$80,000*	$1,360,000	*$80,000*
Installation Cost (mid)	$2,704,400	*$135,220*	$2,000,000	*$100,000*	$1,700,000	*$100,000*
Installation Cost (high)	$3,380,500	*$169,025*	$2,500,000	*$125,000*	$2,125,000	*$125,000*
Total Cost (low)	$3,515,720	*$175,786*	$4,716,000	*$235,800*	$3,315,000	*$195,000*
Total Cost (mid)	**$4,056,600**	***$202,830***	**$5,116,000**	***$255,800***	**$3,655,000**	***$215,000***
Total Cost (high)	$4,732,700	*$236,635*	$5,616,000	*$280,800*	$4,080,000	*$240,000*
Annual O&M Cost	**$30,500**	***$1,525***	**$30,500**	***$1,525***	**$61,200**	***$3,600***

Thank you for the opportunity to complete this work on behalf of UDOT and Fehr & Peers. Should you have any questions or require clarification on the contents of this report, please contact the undersigned.

Report prepared by:

Alan Jones, P.Eng

Reviewed by:

Jordy Hendrikx, PhD.

8.0 References

Alta Ski Lifts. 2009. Preliminary study of alternate avalanche control methods in avalanche paths affecting portions of State Road 210 and the Town of Alta.

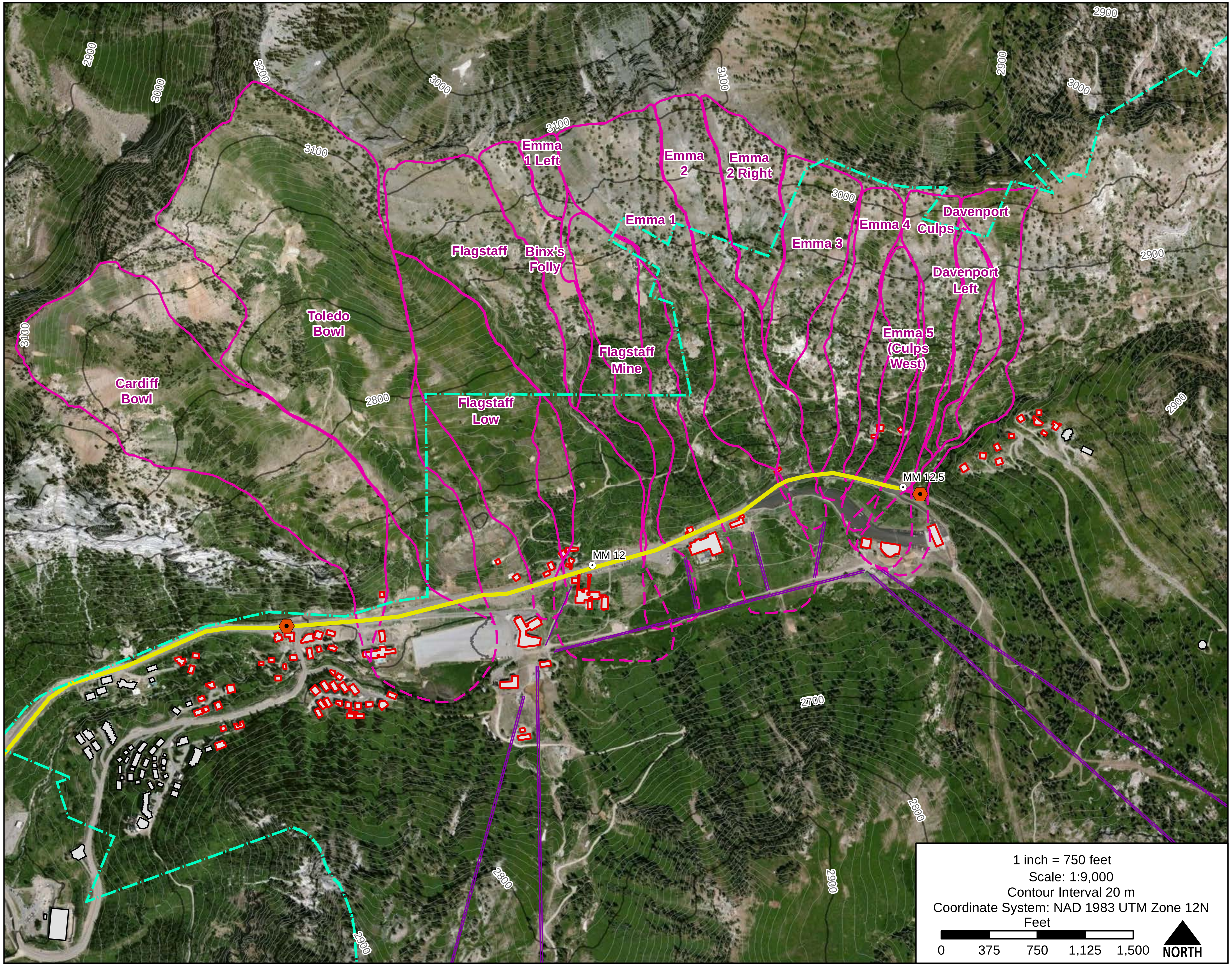
Fehr & Peers Associates (F&P), 2006. Little Cottonwood Canyon SR210 Transportation Study. Final Report. August 2006. Report prepared for UDOT.

HW Lochner, 2006. SR-210 Little Cottonwood Canyon Transportation Study. Technical Memorandum: Rough Cost Estimates for Selected Passive Avalanche Control Measures.

APPENDIX A – Maps

Avalanche Infrastructure Study Above the Town of Alta

Avalanche Atlas



Legend

- Avalanche Atlas Mapping (2016) [1]
- Approx. Runout Extent (2016) [1]

Structures

- Not exposed to overfire in study area
- Exposed to overfire in study area

Infrastructure

- Ski Lift
- SR 210
- Mile Marker
- Closure Gate
- Town of Alta Boundary

NOTES:
Map scale is intended for 11" x 17" paper size. Actual scale may vary depending on printed paper size and printer settings.

Data Sources:
1. Avalanche atlas mapping revised by DAC June 2016 based on avalanche occurence data, 2 meter topographic contours and field observations.
2. Base imagery from Bing Maps.
3. Contours generated from 2 m DEM provided by UDOT.

DYNAMIC AVALANCHE CONSULTING LTD.
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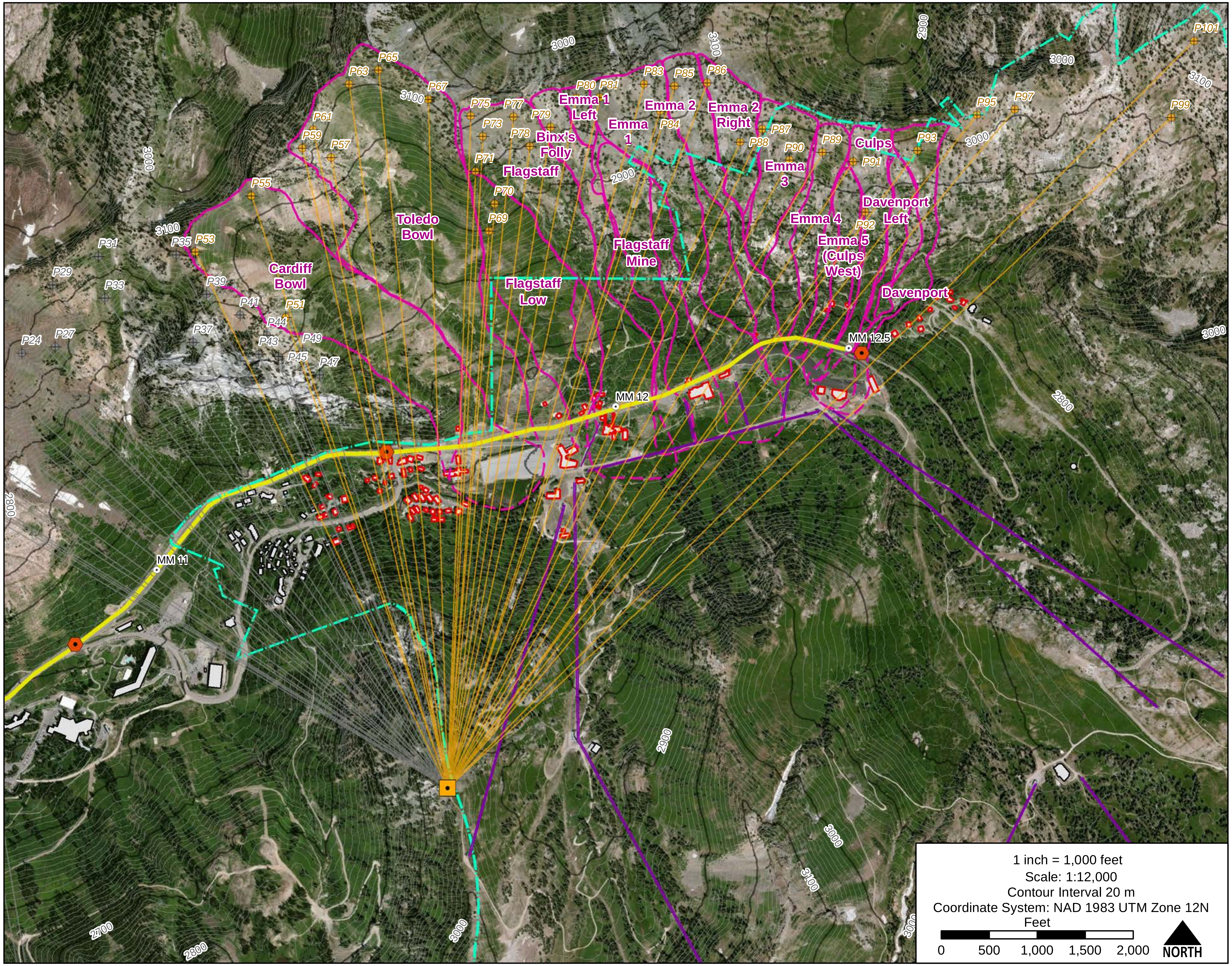
Drawing Number:	16-0014-FPS-001
Date:	30/06/2016
Designed by:	Alan Jones, P. Eng
Reviewed by:	
Drawn by:	Chris Argue, Dipl. T



Avalanche Infrastructure Study Above the Town of Alta

Artillery Program

Legend

- Avalanche Atlas Mapping (2016) [1]
- Approx. Runout Extent (2016) [1]
- Artillery Gun Platform

Artillery Target

- Inluded in study area
- Exluded from study area

Artillery Firing Line

- Inluded in study area
- Exluded from study area

Structures

- Not exposed to overfire in study area
- Exposed to overfire in study area

Infrastructure

- Ski Lift
- SR 210
- Mile Marker
- Closure Gate
- Town of Alta Boundary

NOTES:
Map scale is intended for 11" x 17" paper size. Actual scale may vary depending on printed paper size and printer settings.

Data Sources:
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2. Base imagery from Bing Maps.
3. Contours generated from 2 m DEM provided by UDOT.

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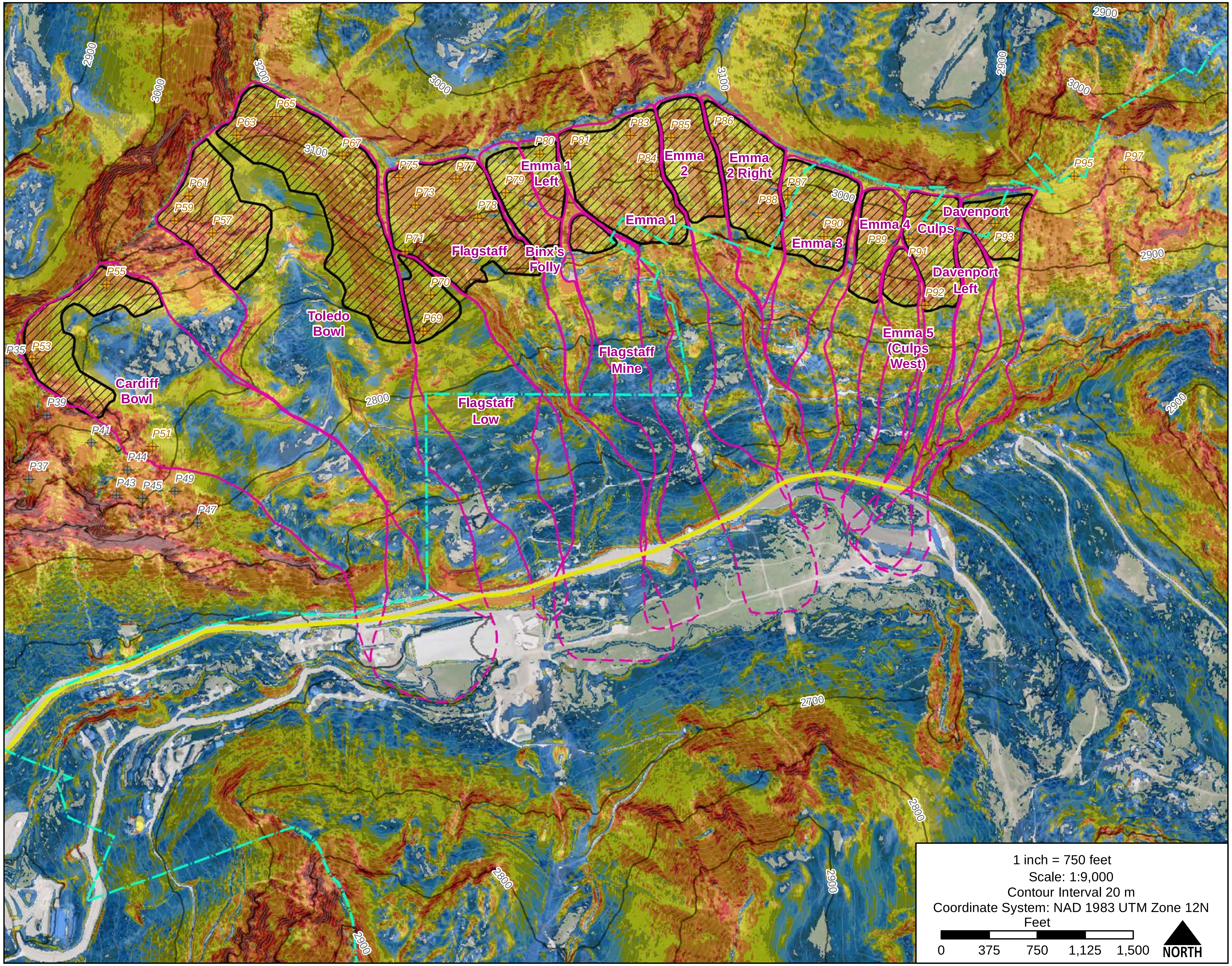
Avalanche Infrastructure Study Above the Town of Alta
Snow Net Areas



Legend

- Avalanche Atlas Mapping (2016) [1]
- Approx. Runout Extent (2016) [1]
- Town of Alta Boundary
- SR 210

Artillery Target

- Inluded in study area
- Exluded from study area
- Snow Net Areas

Slope Class

Angle in Degrees

- 0 - 10
- 10 - 15
- 15 - 20
- 20 - 25
- 25 - 30
- 30 - 35
- 35 - 45
- 45 - 55
- 55 - 90

NOTES:
Map scale is intended for 11" x 17" paper size. Actual scale may vary depending on printed paper size and printer settings.

Data Sources:
1. Avalanche atlas mapping revised by DAC June 2016 based on avalanche occurence data, 2 meter topographic contours and field observations.
2. Base imagery from Bing Maps.
3. Contours generated from 2 m DEM provided by UDOT.

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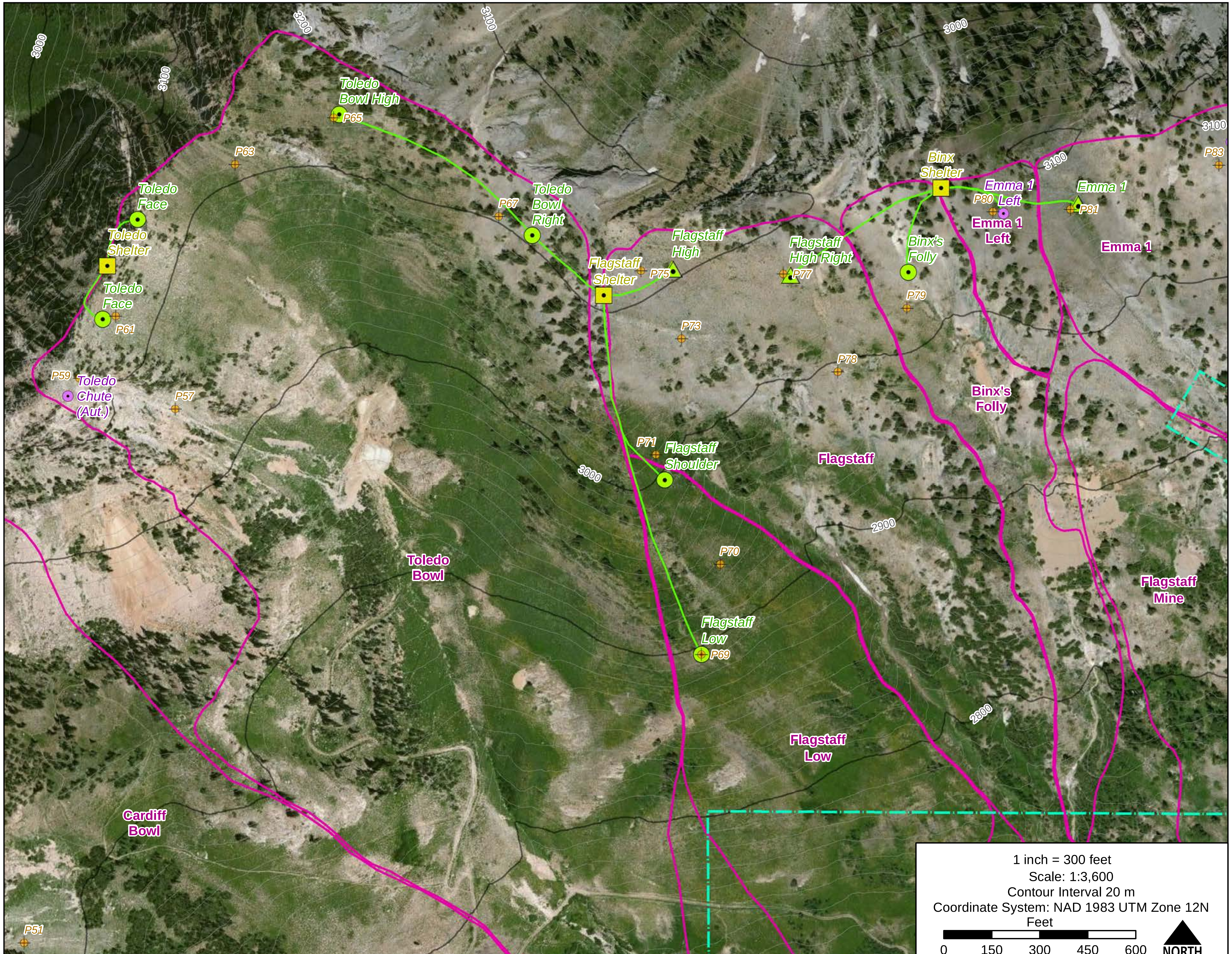
Avalanche Infrastructure Study Above the Town of Alta

Gazex - Toledo to Emma 1



Legend

- Avalanche Atlas Mapping (2016) [1]
- Approx. Runout Extent (2016) [1]
- Town of Alta Boundary

Artillery Target

- Inluded in study area
- Exluded from study area

Proposed Gazex System

- 3.0 m Exploder
- 3.0 m Exploder with Splitter
- 1.5 m Exploder
- 1.5 m Exploder with Splitter
- Shelter
- Gazex Pipeline

NOTES:
Map scale is intended for 11" x 17" paper size. Actual scale may vary depending on printed paper size and printer settings.

Data Sources:
1. Avalanche atlas mapping revised by DAC June 2016 based on avalanche occurence data, 2 meter topographic contours and field observations.
2. Base imagery from Bing Maps.
3. Contours generated from 2 m DEM provided by UDOT.

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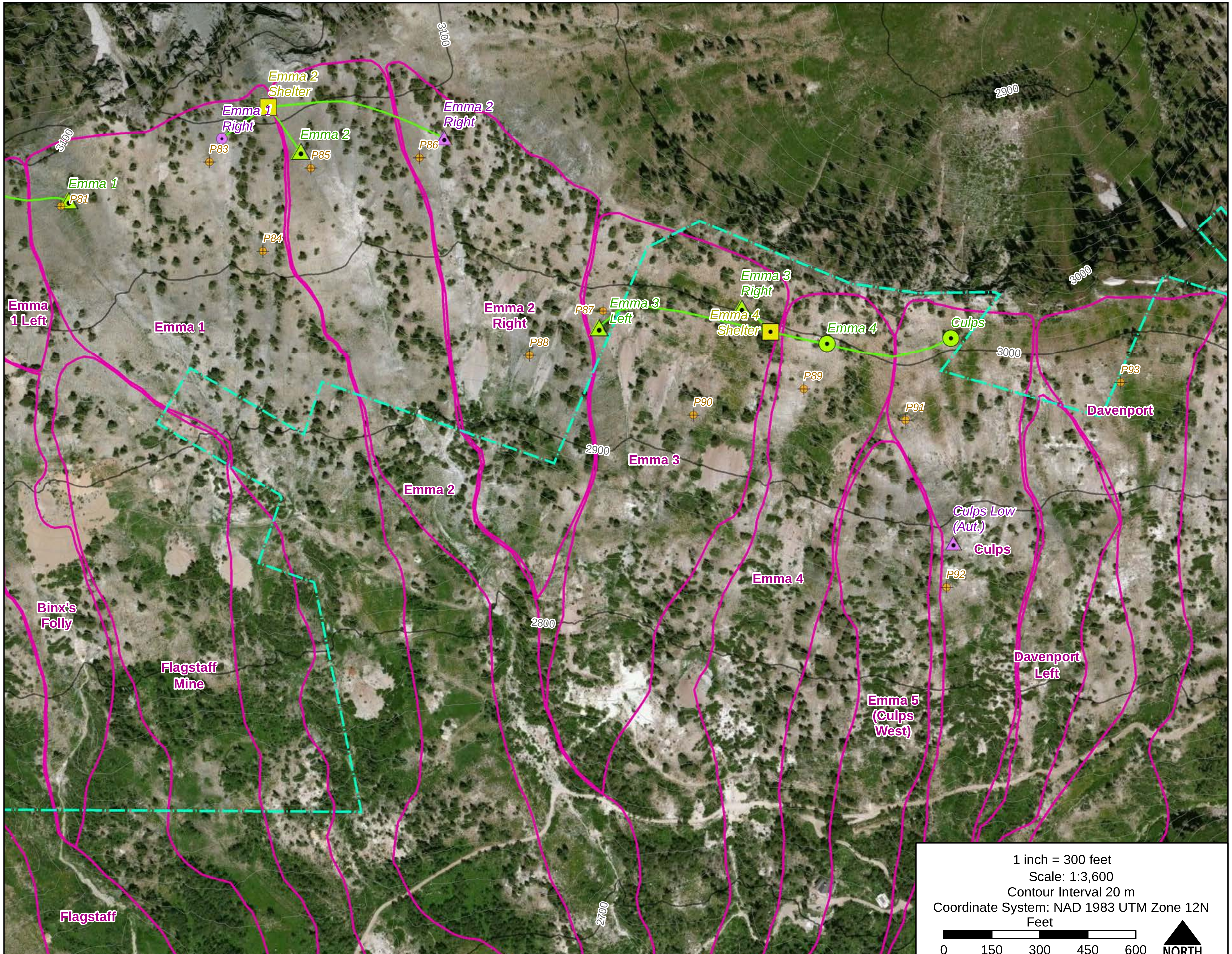
Drawing Number:	16-0014-FPS-004
Date:	30/06/2016
Designed by:	Alan Jones, P. Eng
Reviewed by:	
Drawn by:	Chris Argue, Dipl. T

Avalanche Infrastructure Study Above the Town of Alta

Gazex - Emma 1 to Culps



Legend

- Avalanche Atlas Mapping (2016) [1]
- Approx. Runout Extent (2016) [1]
- Town of Alta Boundary

Artillery Target

- Inluded in study area
- Exluded from study area

Proposed Gazex System

- 3.0 m Exploder
- 3.0 m Exploder with Splitter
- 1.5 m Exploder
- 1.5 m Exploder with Splitter
- Shelter
- Gazex Pipeline

NOTES:
Map scale is intended for 11" x 17" paper size. Actual scale may vary depending on printed paper size and printer settings.

Data Sources:
1. Avalanche atlas mapping revised by DAC June 2016 based on avalanche occurence data, 2 meter topographic contours and field observations.
2. Base imagery from Bing Maps.
3. Contours generated from 2 m DEM provided by UDOT.

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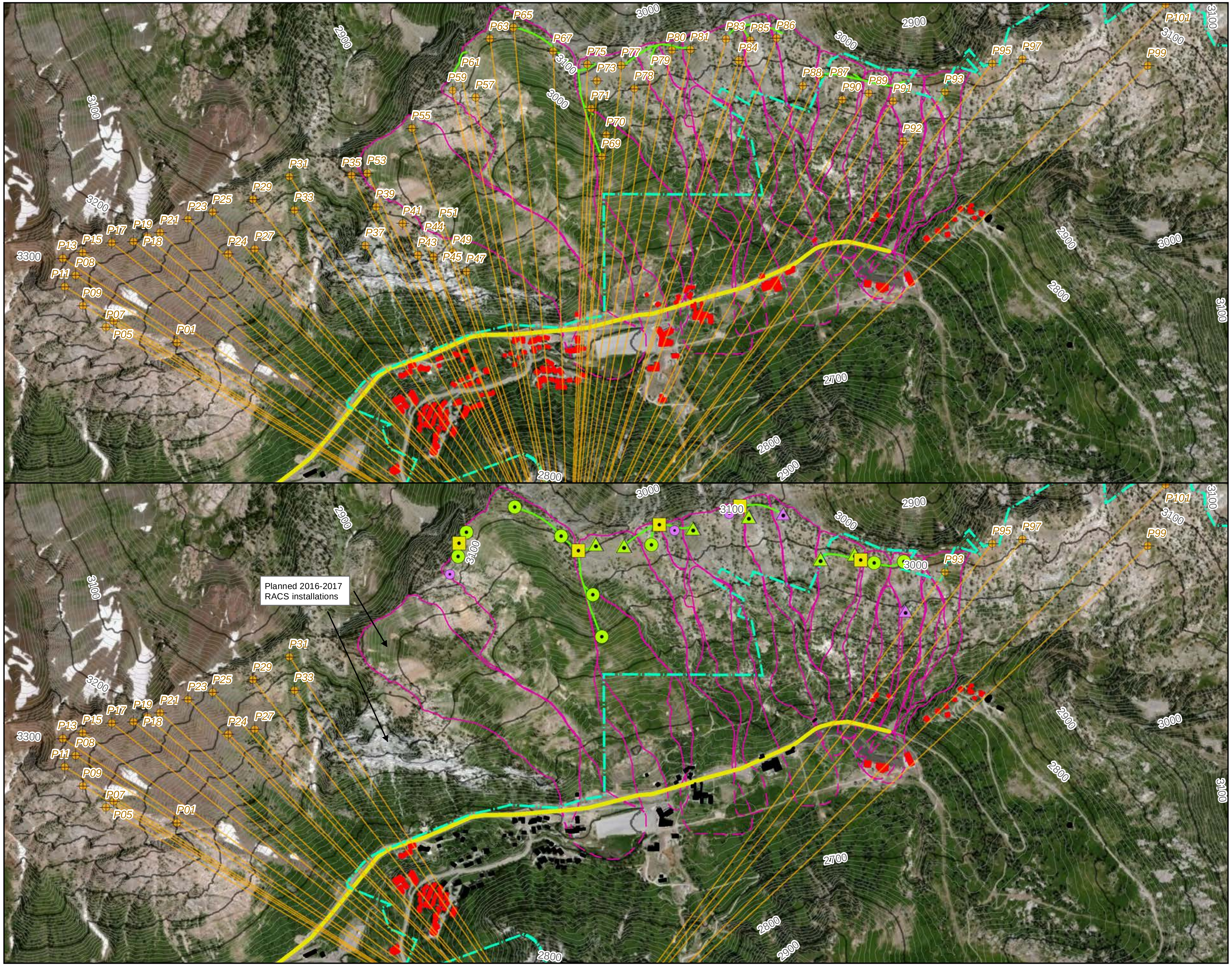
Avalanche Infrastructure Study Above the Town of Alta

Artillery Overfire Reduction



Legend

- Avalanche Atlas Mapping (2016) [1]
- Approx. Runout Extent (2016) [1]
- Town of Alta Boundary
- SR 210
- Artillery Gun Platform

Artillery Target

- Artillery Target
- Artillery Firing Line

Proposed Gazex System

- 3.0 m Exploder
- 3.0 m Exploder with Splitter
- 1.5 m Exploder
- 1.5 m Exploder with Splitter
- Shelter
- Gazex Pipeline

Structures

- Exposed to overfire
- Not exposed to overfire

NOTES:
Map scale is intended for 11" x 17" paper size. Actual scale may vary depending on printed paper size and printer settings.

Data Sources:
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2. Base imagery from Bing Maps.
3. Contours generated from 2 m DEM provided by UDOT.

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APPENDIX B – Visualizations showing potential Gazex RACS locations

Figure B1. Emma 1 potential 3.0 m^3 Gazex location.

Figure B1. Flagstaff Shoulder potential 3.0 m^3 Gazex location.

Figure B2. Emma 2 potential 3.0 m^3 Gazex location.