

REMOTE AVALANCHE CONTROL SYSTEMS (RACS) ALONG THE TRANS-CANADA HIGHWAY - OPERATIONAL IMPROVEMENTS AND CHALLENGES DURING SIX WINTERS OF USE AT THREE VALLEY GAP, REVELSTOKE, CANADA

Walter Steinkogler^{1*}, Alan Jones², and Chad Hemphill³

¹ *Wyssen Avalanche Control, Revelstoke, BC, Canada*

² *Dynamic Avalanche Consulting Ltd., Revelstoke, BC, Canada*

³ *Ministry of Transportation and Infrastructure, Revelstoke, British Columbia, Canada*

ABSTRACT: Three Valley Gap, located 20 km west of Revelstoke, Canada is one of the highest priority avalanche areas on the Trans-Canada Highway (TCH). During 2007-2016, avalanche related closures averaged 46.5 hours per winter during 12 closure periods (average of 4 hours per closure), many of which exceeded 2 hours. These closures presented a major disruption to commercial traffic and the local economy. Increasing traffic volumes continue to increase avalanche risk in this corridor, and compound traffic flow problems. Starting in 2016 eleven remote avalanche control systems (RACS) had been installed at Three Valley Gap. This system reduces risk to public and commercial vehicles, risk to workers performing avalanche control, and the duration of avalanche related closures. This paper focuses on operational improvements and challenges experienced during the last 6 winters since the RACS were added to the program. Benefits of RACS during the first six winters included a reduction of average time for avalanche control from about 30-60 to 10-30 minutes, and the reduction of the average time per closure from 4 hours during 2007-2016 to 1.8 hours during 2017-2023. This is especially relevant as traffic volume has been steadily increasing on average by 2.9% each year, compounded. Additionally, shifting control missions to nighttime or early morning hours and reducing pre-mission preparation time frees up worker resources that allows avalanche personnel to manage other avalanche areas in the highway corridor. Recently, operations have been further optimized with the construction of a dedicated storage building nearby, where the deployment boxes can be stored over the summer and where maintenance and loading are carried out. Technical improvements and location-specific modification of the deployment boxes included snow roofs to avoid snow accumulation on top of the lid and a customized power-safe mode to address the limited solar gain at tower locations. In terms of evaluating the locations of the system, we review the chosen locations and the general effect of explosive airblasts in heavily forested terrain. The findings highlight operational challenges that are relevant to the planning and optimizing of RACS projects, especially in steep, forested, high frequency avalanche paths.

KEYWORDS: Avalanche control, highway, avalanche risk, explosives, RACS, Three Valley Gap.

1. INTRODUCTION

The reliability of highway corridors during winter has a significant impact on both the local and regional economy. For tourist regions, e.g. ski resorts, the disruption of the supply of goods, traveling personnel and tourists can have significant consequences. In western Canada, increasing traffic volumes and public expectations increases pressure on highway managers to keep traffic flowing and reduce highway closures. To achieve more efficient highway closures, a variety of avalanche control measures are applied, including Remote Avalanche Control Systems (RACS). RACS can control avalanches at any time and during any weather conditions, and reduce avalanche magnitude by triggering smaller, more frequent avalanches. RACS are a well-established tool for managing avalanche risks for ski resorts, highways and railways in Europe and North America.

Additionally, private industries, such as mines, are increasingly installing RACS to upgrade their operational avalanche risk management and as economic considerations make their capital investment beneficial.

1.1 Three Valley Gap and project description

The reliability of the Trans-Canada Highway (TCH) corridor through British Columbia (BC), the main traffic route through Canada, is largely driven by avalanche risk during the winter. Three Valley Gap (3VG) is a narrow mountain pass and one of the most active avalanche areas on the TCH. 3VG is located 20 km west of Revelstoke, BC, in a transitional (intermountain) snow climate (Haegeli and McClung, 2003). The project area presented below includes eight high-frequency avalanche paths that can produce avalanches that are hazardous to traffic with as little as 20 mm of precipitation. Rockfall is an additional natural hazard that can occur in the same paths.

* *Corresponding author address:*

Walter Steinkogler, Wyssen Avalanche Control,
Revelstoke, Canada
tel: +41 76 2718858
email: walter@wyssen.com

The terrain in 3VG is steep and densely forested, with gullies that produce frequent avalanches up to Size 3. Once avalanches initiate, they usually reach the TCH due to the steep terrain. (Figure 1).

The safety and reliability of the TCH through 3VG has a direct and significant effect on the economy of the province and the country (Chris Stethem and Associates Ltd., 2010). When closed, traffic is unlikely to seek alternative routes (Morrall, 1995) which would require substantial additional time (e.g. 6 hours or more) and whose reliability is also dependent on avalanche hazard.

Traffic volumes through 3VG have substantially increased in recent decades. Winter average daily traffic (WADT) has increased from around 1000 vehicles per day (vpd) in 1980 to nearly 4000 vpd in 2010. WADT is forecast to reach 6000 vpd by 2030 (Chris Stethem and Associates Ltd., 2010). Approximately 58% of the WADT is composed of heavy commercial vehicles in the winter. The percentage of heavy commercial vehicles is substantially higher in the winter compared to the summer, further highlighting the important of maintaining traffic flow in the winter.



Figure 1: Overview of Three Valley Gap avalanche area and RACS locations (Path 11.7 location not shown).

In 2016, the BC Ministry of Transportation and Infrastructure (MoTI) contracted Wyssen Avalanche Control to supply and install nine RACS in seven avalanche paths during a two-year construction period. Five towers were installed in 2016, followed by the remaining 4 towers in 2017. 2 more tower were added in 2018. This was the first installation of this type of RACS in North America.

The selected RACS (Wyssen Tower) consists of an 8-10 m high steel tower with a steel deployment box on top that can be installed and removed via helicopter without personnel required on-site (Figure 2). Each deployment box holds 12 charge containers with up to 5 kg of explosives.

The RACS is operated from the highway by an avalanche technician using a web-based interface connected by mobile phone network or radio. Towers can be operated individually, or multiple towers can simultaneously deploy charges to control multiple paths at once. Charges are dropped from the deployment box and suspended by a cord above the snow surface. The detonation delivers a 360-degree air blast to the adjacent avalanche start zone.



Figure 2: RACS installation at 3VG overlooking Trans-Canada Highway 1.

2. TECHNICAL IMPROVEMENTS OF RACS

Leading up to the project start, but also during the first operational winter seasons, multiple technical modifications and improvements were made to the deployment boxes.

2.1 Snow accumulation on RACS in forested terrain

Due to the location of the RACS within steep and heavily forested terrain, significant amounts of snow

accumulates on top of the lid of the deployment boxes, typically over a period of multiple weeks. The accumulation would sometimes reach all the way up to the attachment point for the helicopter hanger needed to remove the box from the tower.

This issue has the potential to make removal of the box from the tower very difficult, either until the snow melts or is manually removed by a worker on the tower. Furthermore, the amount of snow can add a significant additional mass to the overall weight. Assuming an average density of 300 kg m^{-3} and 1 m^3 of snow, this would equate to roughly 300 kg of extra weight. Given the weight of the deployment box is 450 kg, this represents an increased weight of 50%. Depending on elevation of the RACS and available helicopter type, this can further complicate transport logistics. As a consequence aluminum snow roofs were developed and added to the deployment box which allows for snow to slide off the roof away from the deployment box. Following implementation of this upgrade, snow accumulation no longer presented a problem.

Generally snow accumulation and snow fall characteristics have to be considered for the design of RACS, for example the snow depth compared to the tower height. The issue described above demonstrates an additional snow related issue that needs to be considered on a site-by-site basis.

2.2 Power consumption

Due to the orientation of the RACS on the steep, forested and north facing terrain, very limited solar input is available especially in December and January. The continuous remote monitoring of voltage at the start-up phase identified that power supply might become an issue. Although the amount of batteries were tripled from the project start and an increase in solar input could be observed once the south facing counter slope was snow covered, a specific low power mode was developed and uploaded remotely on each deployment box. This software modification puts the RACS into a “sleep” mode, which then “wakes up” before a control mission is started. Overall, this modification has proven to be a reliable solution for the 3 Valley Gap area. In areas with even less solar input, special hardware setups were developed for ultra-low power modes (e.g., Mt Stephen, Canada) or added wind generators (e.g., high latitude installations in Norway).

2.3 Communication challenges

Although mobile phone coverage is generally available for the Three Valley Gap area, there is inconsistent coverage in some locations. Relaying via the installed radio between the RACS is a good solution to reach towers in gully shaped terrain features.

However, communication can be very limited if the main mobile phone tower is not operating, which does occur periodically. This was the case once already at 3VG when a semi-truck crashed into the power line and therefore the mobile tower went offline. The RACS automatically connected to the next available mobile tower. Although the connection was sufficient to connect to the towers, it was very much on the limit to have sufficient communication of data to operate the mobile device at road level to the main web interface. For these scenarios it is important to have a reliable back communication in place that also will work without any mobile phone coverage in the area – at 3 Valley Gap and other locations in western Canada this is general via radio communication.

3. CONTROL TIME VS TRAFFIC VOLUMES

The operational benefits of the installed RACS was already observed in the first year of installation (with 4 RACS installed). Jones et al. (2018) discussed risk management improvements such as the substantially reduced pre-mission preparation time, allowing workers to manage other avalanche areas in the highway corridor and conduct avalanche control missions in the dark (typically during early morning hours), when lower traffic volumes are present on the highway (Figure 3), decreasing traffic disruption and thus economic impacts to this important commercial transportation corridor.

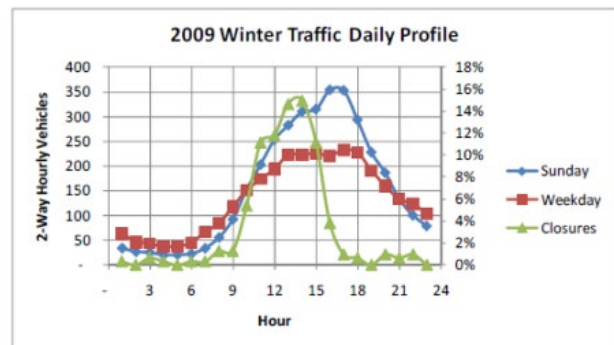


Figure 3: Winter traffic daily profile. Source: Chris Stethem and Associates Ltd. (2010).

Overall the time needed to perform avalanche control reduced from approximately 30-60 minutes prior to 2016 to 10-30 minutes on average in recent years (Table 1).

The distribution of closure times (i.e., duration) has also shifted, such that the number and combined time of short closures (e.g., < 1 hour) have generally increased, while the number and combined time of longer closures (> 2 hours) are reduced compared to historical averages (Figure 3). Yet, some winters, such as 2019/20 and 2021/22 still showed multiple closures >2 hours. These delays were attributed to events that occurred outside the normal operation conditions such as misfire management or larger

amounts of new snowfall and consequently increased snow removal time, avalanches up to size 3, at the highway level.

Table 1: Summary of avalanche closures in 3VG comparing data from 2007-2023 and the first two winters following RACS installation.

	Closures per year	Closure time per year (hours)	Average time per closure (hours)	Time needed to perform avalanche control ¹
Average 2007-2016	12	46.5	3.9	30-60 minutes
Winter 2016/17 (4 RACS)	13	21.7	1.7	5-15 minutes
Average 2017-2023 (11 RACS)	15	30.0	1.8	10-30 minutes

¹Closure times and numbers based on BC MoTI records; times for avalanche control are approximate and do not include securing the road (sweep) and explosives preparation (Visotzky, 2017).

Overall this strategy of shorter closure periods is consistent with the goal of adjacent avalanche areas (e.g. Rogers Pass, 90 km to the east), and the province-wide goal of improving winter highway reliability (combination of safety and accessibility) for the public (Chris Stethem and Associates Ltd., 2010). This approach also helped to reduce the total avalanche related closure times per year from 46.5 hours during 2007-2016 to 30 hours on average in 2017-2023.

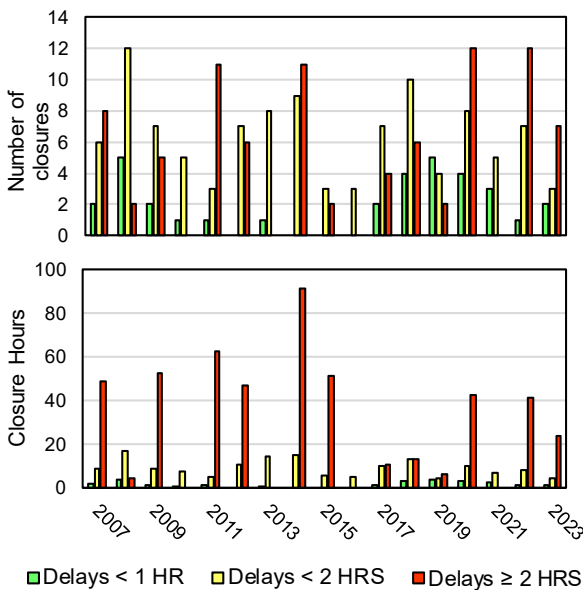


Figure 4: Annual number of closures (upper graph) and closure time (lower graph) for Three Valley Gap during 2007-2018, classified by duration of closure in hours.

The traffic volumes have seen a steady increase of 2.9% per year, compounded over the last 15 years [Vehicles per day (vpd): 2004: 2923 vpd; 2017: 4470 vpd; 2022: 4979 vpd] (Figure 5).

Since the installation of the RACS in 2016 until 2023, an overall increase in winter average daily traffic (WADT) of 6% was observed (Figure 4) while at the same time period a 35% reduction in closure time has been achieved combined with a 55% decrease in average time per closure.

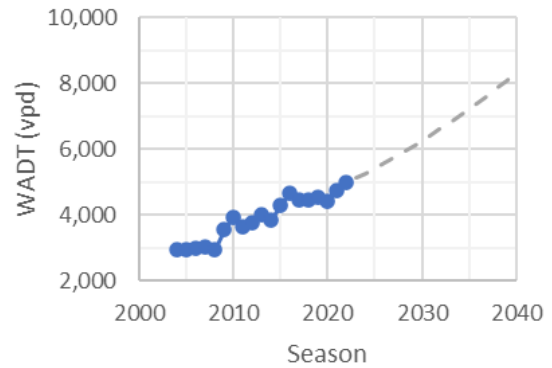


Figure 5: WADT and projected WADT at the 5-year average annual growth rate of 2.9%.

The Avalanche Hazard Index (AHI) (Schaerer, 1989) has been assessed and determined in Three Valle Gap multiple times, most recently in 2022. The AHI was calculated at 163 in year 2010 for WADT of 3625 vehicles per day as presented in Chris Stethem and Associates Ltd. (2010). It was recently re-calculated in year 2022 at 151 for WADT of 5877 vehicles per day (Alpine Solutions, 2022). So, in the past 13 years winter traffic has increased by approximately 60% while the avalanche hazard has essentially remained the same. This demonstrates a continuing improvement in the avalanche hazard management program during this period, despite significantly increasing traffic volumes.

Assuming a continually increasing traffic volume of 2.9% per year (Figure 5), approximately 6800 vpd could be reached by about 2033, which is an increase of approximately 37%. To maintain the AHI at the same level and to even increase the reliability of the highway, this will present an operational challenge to MOTI.

Also other critical transport corridors with high traffic volumes and even more so due to much higher traffic volumes will face similar challenges with respect to natural hazards.

For example, Interstate-70 at the Eisenhower Johnson Tunnels, Colorado, USA has an average daily traffic volume of approximately 40,000 vehicles per day, with closure costs estimated at USD \$1million per hour (CDOT (2022)). Interstate-90 at Snoqualmie Pass, Washington, USA has a traffic volume of over

30,000 ADT, with closure costs also estimated around USD \$1million per hour (WSDOT (2008)). Wyoming Highway 22 over Teton Pass, Wyoming, USA has a volume of 8,000 ADT, with an estimated cost of USD \$20,000 per hour for closures. Little Cottonwood Canyon, Utah, USA has volume over 9500 vehicles on a peak day in winter; Gotthard highway in Switzerland has 20,000 vehicles per day (20% increase in traffic each year) (FEDRO, 2022). Also closures of smaller roads with somewhat lower traffic volumes (e.g., the main road to Davos, Switzerland with 10,000 vpd) can have significant effect on the local economy. E.g., if personnel or supplies cannot be delivered to tourism regions in the mountains. The financial effect of, especially extended, closures to the economy can be significant (Jones et al., 2018).

4. OPERATIONAL LEARNINGS AND IMPROVEMENTS

4.1 Optimized control timing

With any avalanche control, the timing is critical. Ideally, avalanche control can commence during times of reduced traffic volumes, i.e. night time hours, or early morning. Anchoring on a specific time works well operationally for scheduling staff for the shoot, traffic control, and deposit removal but doesn't always work with the timing of natural avalanche activity. It takes approximately 2 hours to establish a full highway closure on the TransCanada Highway at Three Valley Gap. During periods of intense snowfall and loading rates, MOTI will close the 3 Valley Bluffs danger area while traffic control is positioning and getting ready to implement the full highway closure. Considerations that affect the initiation time of control include:

1. Shoot too early and you miss entraining the full mass of the desired avalanche, and have to shoot targets again before the storm is over.
2. Shoot too late and the risk of having an event involving the travelling public remains.
3. Shoot too often and you risk running out of shots in the RACS for the winter necessitating a reload.
4. The larger the avalanche brought down, the longer the highway remains closed for deposit removal.
5. Shooting multiple towers at once reduces control time (individual detonation confirmation of each RACS).

In March 2022/23, only 2 charges in each tower were remaining. Therefore two helicopter control missions during daylight hours were conducted to save the remaining charges for a night time control mission. This negated the need to reload the towers late in the season with uncertainty of residual storms requiring

control. When freezing levels rise or during periods of rain, snow can melt adjacent to the towers. The lower elevation towers may not initiate avalanches from the rocky start zones while instability may still exist in the gully features and in the higher start zones. Helicopter control will be utilized during these situations and charges deployed directly into the gully features.

4.2 Weather and snow

Snow load bias: 18-20 mm of precipitation (rain gauge measured at road elevation) once the avalanche track is filled in with snow seems to be a good threshold for Size 2.0 avalanches to occur. This changes regularly with temperatures, and wind loading. Higher density snow that bonds to a settled snowpack may not produce avalanches until 25-30 mm of load. Higher density snow falling on a cold or faceted snowpack may produce avalanches quickly (e.g., on March 2, 2023 there was a cycle triggered with 7 mm of recorded precipitation). MOTI technicians record 24h HN, HST and HSB with hourly outputs.

Wind loading in Three Valley Gap is very challenging to forecast due to the venturi effect of the mountains through the corridor. Wind values can vary greatly from highway to start zone elevations and it is common to have wind directions in the start zone oriented 180° from the prevailing wind direction. Spin drift avalanches and blowing snow reduce visibility for highway users, which can create additional hazards.

Temperatures fluctuations between highway level (510 m ASL) and the upper start zones (1160 m ASL) produce varying densities of HST. During prolonged warming periods or rain, the snow on the lower rock bands can melt significantly. Many of the Wyssen tower placements are on rocky outcrop features that entrain snow from the gullies (tracks). During these warming periods, there may be little snow around the Wyssen Tower targets to initiate avalanches. Larger spring loose wet avalanches and wet slabs are possible through April and testing of these areas is completed with helicopter control.

4.3 Loading and maintenance facility

The support building was constructed in the main loading and staging area 3 km west of the 3VG bluffs. The building allows MOTI to have a secure site to store, maintain and assemble the charges for the deployment boxes (Figure 1). Propane heaters help with working temperatures and warm the building in November during the loading. This also helps with pliability of the components. The plastics of the charge containers are less brittle and prone to

breaking clips at warmer temperatures. The safety fuse assemblies bend easier when they are warm, and are less prone to kinking and disruption of the black powder train at warmer temperatures.



Figure 6: RACS loading and maintenance facility close to Three Valley Gap.

In November 2022, loading operations had to be suspended due to unfavourable flying conditions. Four deployment boxes were already primed, loaded and ready to fly to the towers. Due to the secure building, MoTI could employ a security company to guard the building from the outside without them needing Natural Resource Canada explosives clearance. This was because they had no access to the building. MOTI Avalanche Technicians guarded the building until 18:00, then the security detail worked from 18:00-06:00. Work recommenced and the loading procedure was completed the following day. Without a secure building, explosives would either need to be disassembled or guarded overnight in an outdoor location.

4.4 Explosives airblast in forested terrain

Before the installation of the RACS, avalanche technicians had to deploy explosive charges from the helicopter onto small benches in the terrain whenever flying conditions allowed. With the RACS control can be performed at any time of day and when snowfall accumulations exceed thresholds. Even though the trees seem to reduce the range of the explosive airblast, the effect at 3VG shakes snow from the trees which consequently flows into the path and entrains and removes snow until it reaches the highway. A qualitative assessment of videos indicates that the snow removal from trees seems to be very effective for a range of at least 50 m laterally from the tower (Figure 6).

4.5 Misfire and dud management

Misfires can occur with any type of RACS system for a variety of reasons and result in partial detonations, no ignition (e.g., due to non-working safety fuses and detonators) or dropped and non-ignited charges

(e.g., due to loading error). To ensure the slope is affected with the intended force of an explosive detonations the system has to be able to detect whether the charge detonated.

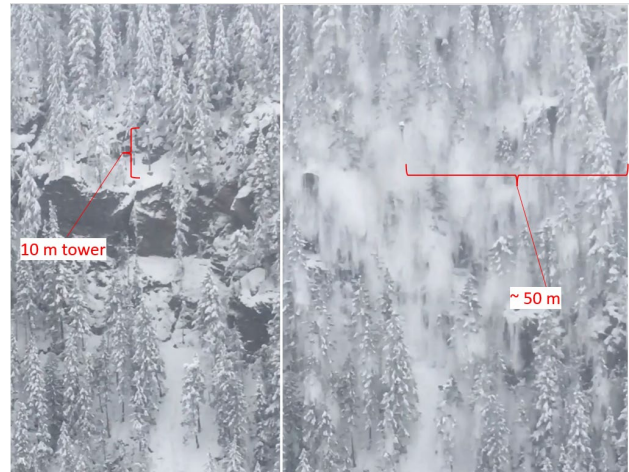


Figure 7: Explosive airblast effect in heavily forested terrain generally exceeds 50 m.

The very steep and rocky terrain at Three Valley Gap make a mitigation of a misfire by placing an additional charge from a helicopter very difficult. Experience has shown that when cut away from the tower, the charge container holding the explosives will sometimes break into pieces once it hits the rocks below the tower and in the path. Consequently a safety bulletin and supervisor training were conducted with the maintenance contractor to identify any explosive charges during deposit removal, with a clear procedure for reporting.

4.6 Traffic management

Three Valley Gap is a very difficult piece of terrain to manage and forecast for snow avalanches that affect the highway corridor. The highway is single lane each way, with the steep bluffs on one side and a lake of the other. There is little catchment available to keep avalanches from affecting the travel portion of the highway and powder avalanche events can contribute to Motor Vehicle Incidents (MVI's). The direct action avalanche paths cannot handle rapid loading from snow and/or wind and can begin flushing avalanches with little warning.

Since the installation of RACS in 2016, procedures have been developed to reference the different conditions that lead to avalanche cycles. Early recognition of threshold snow amounts is required to activate resources to enact a closure and avalanche control. Careful monitoring of active sloughing is required while traffic control personnel is setting up the closure (approx. 2 hours to set up a full closure). Dust events affecting traffic can lead to motor vehicle incidents within the avalanche area. Stopped traffic can

back up quickly in the danger area and lead to a complex response to clear the area prior to commencing avalanche control. During these times, MOTI staff are stationed at each end of the bluffs to be able to stop traffic at a moment's notice.

Shifting closures and control work out of peak traffic times has helped to avoid running out of vehicle storage in adjacent ponding areas.

4.8 *Multiple hazards*

In addition to the snow avalanche other natural hazards exist at Three Valley Gap – rockfall being one of the most difficult ones to manage. In addition to the RACS, a rockfall net positioned as drape along the rock bluffs was installed. Rocks will hit the drape and follow its contour into the ditch at the side of the highway instead of hitting the road directly. Operational experience has shown that the nets still allow the avalanches to flow through and snow removal at the base of the nets can occur (Figure 7).



Figure 8: Avalanche debris removal at the rockfall drape net at Path 19.7.

5. CONCLUSION

The Three Valley Gap project has demonstrated that a substantial reduction of risk for the public combined with an increase in reliability of Highway 1 could be achieved with a positive cost-benefit ratio of return on investment in six years of operation. The Avalanche Hazard Index remained at a similar level between 2010 and 2022, whereas at the same time traffic volumes increased significantly during this time.

Overall experience showed that especially for complex RACS projects such as at Three Valley Gap, the design phase has to account for local terrain, snow and weather conditions combined with technical characteristics of the system (communication, power supply, etc.). Steinkogler (2016) concluded that RACS projects should consider the right location (=

planning) at the right time (= operation) with the right effect (= effectiveness of the system).

To optimize operations of RACS, the general logistics, such as storage, transport and loading, have to also be considered. A permanent storage and arming building increases worker safety and product reliability by minimizing operator errors during loading. Generally it can also be concluded that installing RACS is not enough as there needs to be an experienced operator forecasting for the region and effectively operating the RACS.

6. OUTLOOK

The build out of the Three Valley Gap area with RACS is expected to be near completion with 11 units installed. Future combination with local mitigation measures, such as catchment improvements, as well as improved detection systems could further optimize the overall system performance and improve highway reliability.

Worker safety and simplified handling could be achieved by implementation of non-explosive bi-component charges or explosive charges that are not primed until detonation. These types of systems are being used in other jurisdictions (e.g., Europe), but currently are not yet approved for use in Canada.

Smart software developments should simplify operational usage as much as possible (Meier et al. (2018)). They already allow for remote support and troubleshooting by the supplier to optimize availability of the RACS. In the future “smart data” could support decision making of operators, e.g. due to additions, such as weather stations, laser, cameras to RACS.

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