LOOKING BACK—30 YEARS OF IMPACT: A CALTRANS GAZEX RACS HISTORY INTERNATIONAL SNOW SCIENCE WORKSHOP 2026, WHISTLER, CANADA

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ABSTRACT: Since its introduction in the early 1990s, Gazex Remote Avalanche Control Systems (RACS) have become a central component of avalanche hazard management on several California mountain highways. Prior to the adoption of Gazex, the California Department of Transportation (Caltrans) relied heavily on artillery and hand-delivered explosives to mitigate avalanche hazard, with thousands of rounds fired from 75 mm recoilless rifles each year. Aging military ammunition and increasingly poor reliability ultimately created a need for an alternative mitigation system. Caltrans began installing Gazex exploders in 1992, with early installations at Echo Summit, Carson Spur, Carson Pass, and the June Lake area. Over more than three decades of operation, these Remote Avalanche Control Systems have changed not only the tools available to Caltrans but also the program's efficiency, safety, timing and the greater philosophy of its avalanche program. Operations that were historically more reactive and labor intensive can now be conducted proactively, rapidly, and with substantially less personnel exposure. Many lessons have been learned during Caltrans tenure with Gazex systems. In the early days, operations were characterized by inadequate maintenance, unnecessarily frequent firing, and limited protocols or documentation. A renewed emphasis on yearly maintenance, and a year-round team of dedicated avalanche personnel has increased system firing reliability to greater than 99% reliability on the present day shot rate amongst all 53 of the state's exploders. This paper examines more than three decades of RACS use within Caltrans, and the continuing role of conventional and remote avalanche control methods within a modern highway avalanche program. We will discuss the operational problems that led to its adoption, lessons learned during implementation, changes in mitigation strategy and efficiency, lessons learned, and the limitations that remain with the widespread use of remote avalanche control.

KEYWORDS: GAZEX, remote avalanche control, highway avalanche mitigation, Caltrans, avalanche safety, RACS

1. INTRODUCTION

Avalanche mitigation on mountain highways presents a distinct operational challenge. Unlike a ski area, a transportation agency must manage avalanche hazard across long corridors, often beneath avalanche paths originating on adjacent public lands, while balancing worker safety, highway closures, mobility, and the practical limitations of available control methods.

The California Department of Transportation (Caltrans) currently maintains significant avalanche programs in three districts in the Sierra Nevada. District 3 manages avalanche terrain around the Lake Tahoe region, including U.S. Highway 50 at Echo Summit. District 9 manages U.S. Highway 395 near Mono Lake and Lee Vining Hill as well as State Route 158 near June Lake. District 10 manages State Route 88, including Carson Pass and Carson Spur. Together, these programs regularly monitor and mitigate approximately 105 avalanche paths in 18 different zones throughout the state.

Today, RACS are an important part of those programs, but this was not always the case. The evolution of Caltrans avalanche mitigation from hand charges and military artillery to Gazex provides an example of how modern mitigation technology can change not only how avalanches are triggered, but how an entire avalanche program approaches forecasting, staffing, maintenance, highway closures, and worker exposure.

This paper examines how more than 30 years of RACS operation have influenced Caltrans avalanche program strategy, maintenance practices, staffing, worker exposure, and the integration of complementary mitigation methods. Particular attention will be given to the operational lessons learned from long-term use of these RACS. This discussion will be based on a retrospective review of the Caltrans avalanche program, combining historical information with operational experience. Operational observations and historical figures are primarily based on interviews

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with Rob Bickor, Caltrans Area Superintendent and Avalanche Specialist.

2. CALTRANS AVALANCHE CONTROL BEFORE GAZEX

Avalanche control by Caltrans began in the early 1950s on Highway 50 at Echo Summit. This program expanded to State Route 88 alongside construction and development of the Kirkwood Mountain resort in the late 1960s and early 1970s. Maintaining winter road access to the developing Kirkwood community and ski area required Caltrans to actively manage avalanche hazard along the highway. Previously only opened during the summer, this road to Kirkwood opened year-round in 1972. Early mitigation in these areas relied heavily on hand charges and 75 mm recoilless to keep these roads open throughout the winter.

Figure 1: Caltrans 75 mm recoilless rifle at Carson Spur,1978.

The 75 mm artillery program quickly became the primary component of the avalanche control program, with thousands of rounds fired every year (Bickor, 2026). Although artillery provided the ability to reach avalanche starting zones from a long distance, the system carried significant operational limitations. Available ammunition consisted largely of military surplus dating to the Korean War. Dud rates became increasingly common, and reliability of this artillery became a significant concern. Caltrans was operating a critical avalanche control program around this aging and increasingly unreliable ammunition supply.

Hand-delivered explosives were also a key component of the early Caltrans avalanche program. While this remains a component of their current operations, hand charges are now generally reserved for high-intensity storms with unusual loading patterns, and cornice mitigation in the spring. Their continued use of this conventional method demonstrates an important characteristic which the Caltrans program shares with many avalanche programs globally: no single mitigation tactic provides complete coverage of every avalanche problem.

3. ADOPTION OF GAZEX

By the beginning of the 1990s, the declining reliability of 75 mm ammunition had created a strong incentive to develop an alternative strategy for avalanche control operations. Gazex, then a relatively new European remote avalanche control technology, offered Caltrans a fundamentally different approach. The first Gazex prototype was installed in 1987, followed by the first major installation in 1988 (Lieberman, 2002). Rather than positioning workers or artillery for each mitigation mission, permanently installed exploders could be fired remotely from a controlled safe zone whenever conditions warranted. Gazex uses a mixture of propane and oxygen delivered from an upslope shelter, typically on a ridge or protected bench.

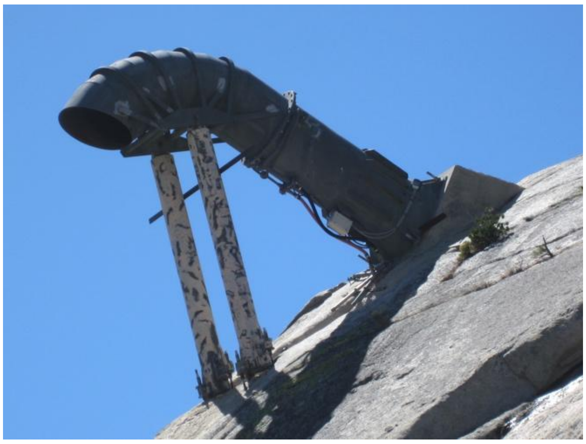

Figure 2: Original standard Gazex exploder at Echo Summit

With the press of a button from a base computer, the pre-dosed propane-oxygen mixture is transferred from the gas storage shelter to the exploder through dedicated pipelines. Once the required mixture has filled the exploder chamber, a spark ignition produces a high-pressure gas expansion and explosive shockwave above the snowpack (Lieberman, 2002).

To back-up and supplement the new and relatively untested technology of Gazex during this operational transition of the early 1990s, Caltrans purchased four 80 mm LoCats for their program. These pneumatic projectile systems also allowed for “filling in the gaps” of slope mitigation left from the initial layout of their Gazex exploders. At present day, three fixed LoCat installations remain associated with avalanche programs in Districts 3 and 10.

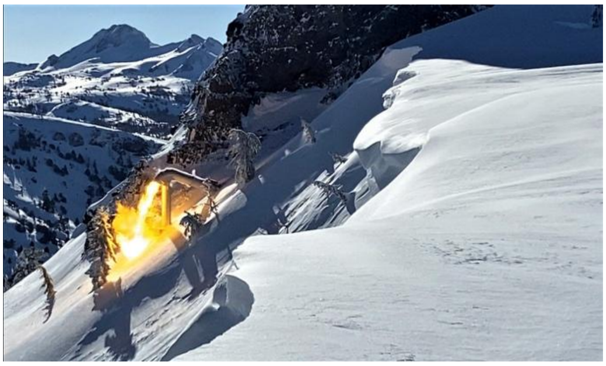

Figure 3: Gazex exploder Firing at Carson Spur.

The initial Caltrans exploders were installed at Echo Summit in 1992, followed by Carson Spur in 1993 and Carson Pass in 1994. Systems were also installed in the June Lake area during this same period. The early systems used standard Gazex exploders positioned in established avalanche starting zones. Carson Spur originally consisted of 12 exploders and has since expanded to 16. Echo Summit has retained 14 exploders, nine at Carson Pass, and Mount Downs near June Lake has 5. Lee Vining Hill represents the most recent complete Caltrans Gazex installation with nine exploders installed in 2007. These 53 Gazex exploders remain in operational use today.

Reliability was the central problem Caltrans was attempting to solve. The 75 mm recoilless rifle program was discontinued after the mid-1990s as Caltrans increasingly relied on remote systems and pneumatic artillery. The transition, however, demonstrated that installing a remote system was only the beginning of developing an effective remote avalanche-control program.

4. GROWING PAINS, AND THE PROBLEM OF THE “EASY BUTTON”

One of the most important lessons from Caltrans’ early Gazex experience was that making avalanche mitigation easier did not automatically make an avalanche program better.

Compared with artillery or hand charges, Gazex was extraordinarily easy to operate. A control mission that once required multiple dedicated personnel, live explosives handling, equipment setup, and exposure to severe winter weather could suddenly be initiated remotely in a controlled environment.

That convenience created what Caltrans Avalanche Specialists describes as the “easy button” trap. Exploders were fired frequently, sometimes based largely on incremental snowfall rather than a deliberate assessment of snowpack and avalanche conditions. While certain avalanche programs in the U.S. have successfully adopted this philosophy (e.g. NVDOT on Mt Rose Highway), in the case of Caltrans, they were not prepared for this excessive use. Lack of maintenance combined with heavy wear and tear created numerous problems in the program’s first decade of RACS use. Additionally, the easy nature of pushing a button from a truck to make an avalanche led to lack of organizational protocols, and minimal documentation to keep track of operations.

When Rob Bickor became involved with the Caltrans program, the original Gazex equipment was relatively young but already experiencing significant problems due to little preventative maintenance during the offseason. Bickor recalls the Gazex system firing reliability to be upwards of 75% at the time his tenure began around 1999. In retrospect, Bickor identifies greater attention to maintenance from the beginning as perhaps the single most important improvement he would make to the original program.

This experience reinforced a lesson that has remained important throughout the program: remote avalanche control does not eliminate the need for avalanche expertise. Instead, it shifts some of the work from individual control missions toward forecasting, system maintenance, documentation, and long-term asset management.

The staffing structure at the time made the need for maintenance particularly important. In the early years, the Caples Lake maintenance yard closed for approximately six months each year. As the Gazex program matured, its year-round maintenance needs helped justify year-round positions, providing continuity for preventative maintenance, upgrades, and operational readiness.

After the successful push for a maintenance program for the Caltrans RACS, their investment has seen substantial improvement. Caltrans now reports firing reliability greater than 99%. Among over 500 Gazex firings among all exploders in an average year, Bickor reports that only one or two times a year they encounter an exploder that failed to fire. Some of the oldest equipment has also substantially exceeded the service life originally anticipated for the equipment; most exploders at Carson Pass remained in service for roughly 32 years before their replacement in the summer of 2026. A similar pattern was documented by WYDOT: early Gazex installations experienced gas leaks, weld failures, manifold failures, and ignition problems, while diligent offseason maintenance, leak detection, and preseason test firing were identified as keys to reliable winter operation (Yount and Gorsage, 2016).

5. FROM REACTIVE TO PROACTIVE MITIGATION

The most significant effect of Gazex may be less about the explosive itself than about the timing of avalanche mitigation. Historically, artillery-based highway avalanche operations would often be highly reactive. Crews were stretched thin during storm cycles, often unable to justify the personnel and logistical commitment required for a control mission until an avalanche reached the highway. Artillery operations required workers to be positioned at the gun mount, while hand charging required multiple personnel to access avalanche terrain. Severe weather—the same conditions producing the avalanche problem—could complicate either operation.

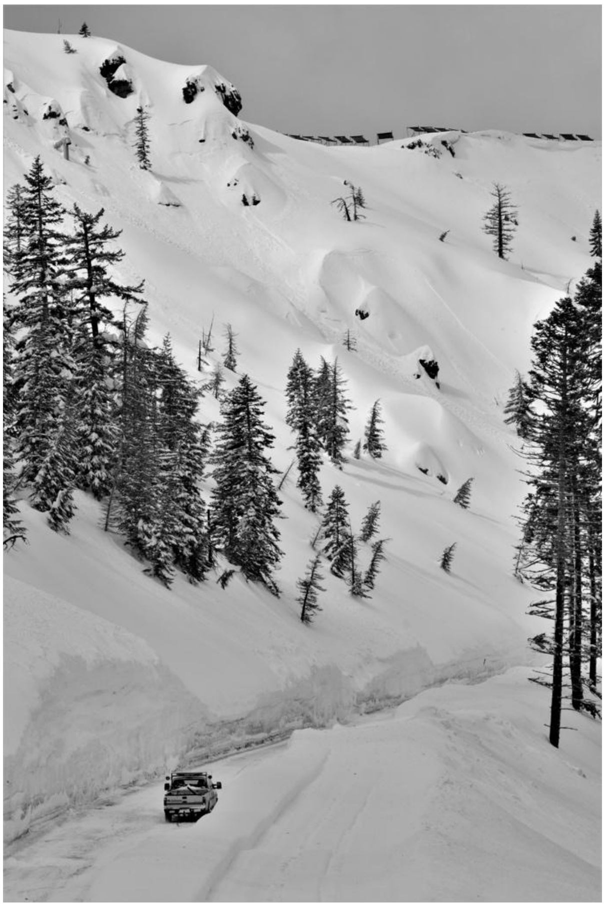

Figure 4: State route 88 beneath the Carson Spur avalanche paths, 2023..

Fixed remote systems changed that equation. Gazex have allowed Caltrans to conduct mitigation more readily when forecasting indicates it is warranted, rather than waiting until conditions justify mobilizing a larger control operation. This has supported a transition from primarily reacting to avalanche events toward proactively managing developing instability. An additional result of this transition is significantly decreased road closure times. At Carson Spur, all 16 Gazex exploders can be fired in approximately 15 minutes (Bickor, 2026). A closure can still take several hours depending on the avalanche results and clean-up required, but the control portion of the operation has seen tremendous gains in efficiency.

The later addition of two Gazex exploders at Carson Spur in 2017 illustrates the operational effect even at a small scale. The two units were installed in locations that historically required regular hand charging. Reaching those locations required more than an hour of personnel access. Fixed exploders now allow those starting zones to be managed remotely with the other slide paths, eliminating repeated field access and saving substantial time over the course of a winter.

6. GAZEX WITHIN A MULTI-TOOL PROGRAM

Despite its operational advantages, Gazex has not eliminated conventional avalanche control methods from Caltrans operations. Instead, the system functions as one component of a broader mitigation program.

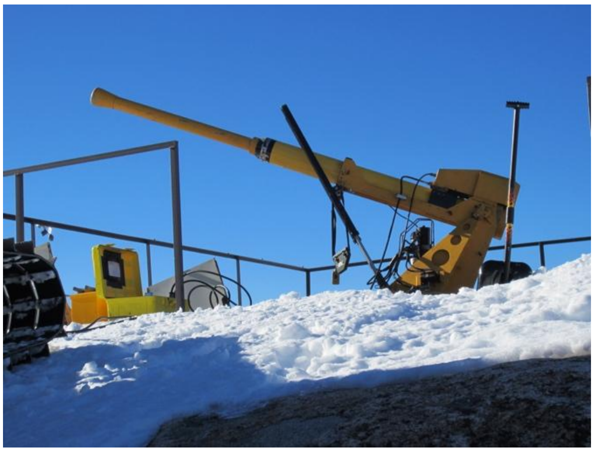

Figure 5: Caltrans LoCat at Carson Spur, 2010.

The LoCat remains valuable where terrain geometry prevents adequate Gazex coverage or where snow accumulation may compromise fixed exploders. These Locat’s use compressed air at up to 3,000 psi to launch explosive projectiles at distances up to 2.2km for Caltrans’ furthest shot placement. Hand charges are used during storms with unusual loading patterns, in areas not covered by remote systems, and for specialized problems such as cornice development.

Caltrans also acquired a DaisyBell system in the winter of 2023 following significant avalanche problems statewide and that season’s extensive helicopter bombing operations. The role of this DaisyBell system is to more effectively and efficiently manage a wide area of big terrain that becomes a concern to the roads during periods of significant snowfall and high to extreme ava-

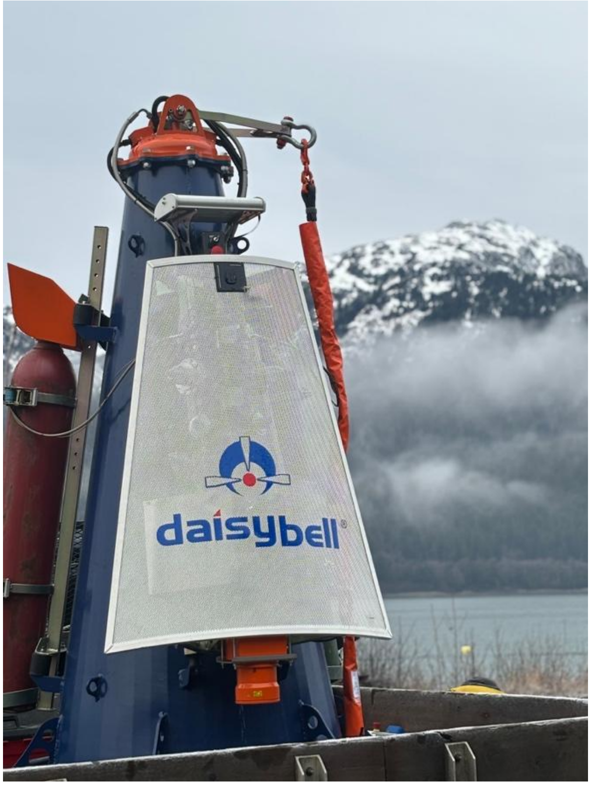

Figure 6: Daisybell system.

lanche hazard. This system therefore joins the operational plan when control is needed for slide paths that do not require regular management throughout a typical winter.

The continued use of multiple systems illustrates an important limitation of remote avalanche control: a fixed installation can only affect the terrain for which it was designed. Avalanche paths with infrequent activity, unusual starting zones, changing snow distribution, or poor access may require different strategies. Caltrans must also decide whether the expenses of permanent mitigation infrastructure are justified on slide paths that do not regularly impact the highway.

7. WORKER SAFETY AND OPERATIONAL EXPOSURE

A principal advantage of Remote Avalanche Control Systems is their ability to reduce the amount of time avalanche workers spend in or immediately adjacent to hazardous terrain. In Caltrans' experience, the transition toward Gazex has substantially reduced the personnel required for many control missions and eliminated the need for repeated field access at specific locations. Bickor notes that near misses and close calls have decreased dramatically since the introduction of RACS to their operations. Gazex did not remove worker exposure entirely, but it changed where and when that exposure occurs.

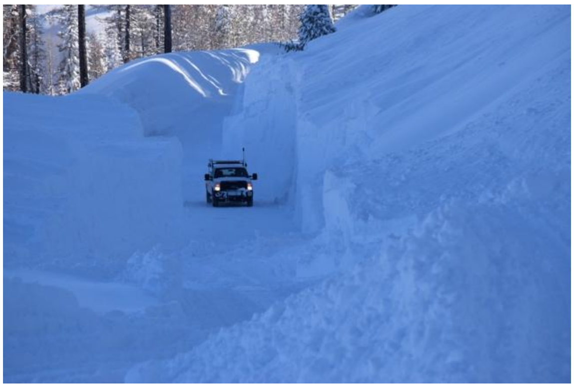

Figure 7: Snow-removal operations at Carson Spur, 2023.

Historically, worker exposure was not limited to the moment an avalanche was intentionally triggered. Conventional operations created exposure during access and egress, artillery setup, hand-charge placement, and recovery of unexploded ordnance. With RACS, many of these hazards are no longer a factor.

After more than three decades of remote avalanche control, the change in acceptable exposure has become embedded in normal operations. Bickor notes that this difference is difficult for current personnel to recognize because Gazex has been part of the program for so long. Nevertheless, the operational contrast is significant: work that once routinely required personnel at a gun mount or in avalanche terrain can now often be completed from a protected location by a single qualified operator.

8. LIMITATIONS AND LESSONS LEARNED – DESIGN, MAINTENANCE, SITE SELECTION (SNOW DEPTH AND EFFECTIVE RANGE), AND BACKUP MITIGATION STRATEGIES

More than 30 years of Caltrans RACS operations have demonstrated that Gazex is not a complete solution to their highway avalanche hazard. Its effectiveness depends equally as much on system design, installation, maintenance and local knowledge of the terrain and snowpack as on the exploder itself. For the program and system effectiveness to evolve and improve, there must be operational willingness to adapt and invest in system design upgrades over time, from mechanical components to communication systems.

Early equipment exposed several design and maintenance lessons. For example, original exploders from the early 1990s did not have drain holes in the tubes. Wind could blow snow into an exploder, wetting the spark plugs and contributing to misfires or delayed firings. Gas-supply infrastructure created a separate set of problems: buried polyethylene pipes could get damaged by wildlife, and above-surface steel pipelines proved difficult to repair. While the type of pipe used has changed since the early days to address these issues, the pipelines which bring gas from shelter to the exploder remain a critical component of the system installation. Through their tenure with this infrastructure, Caltrans has learned the importance of quality installation and careful oversight of the contractor or team doing the install. If installed improperly, the pipelines can lead to very challenging and time-consuming troubleshooting and fixing, especially once the terrain is blanketed with snow.

Maintenance is another limitation these RACS present. Remote systems are permanent infrastructure installed in severe alpine environments and require continuing inspection, repair, gas supply, communications support, and parts replacement. Historically, parts availability and technical support in North America were major challenges for Caltrans, although Bickor reports that U.S. support and local parts availability from the manufacturer have improved substantially in recent years. Caltrans has also experienced problems with previous battery-pack suppliers and has developed multiple generations of in-house communications systems as technology and support have evolved.

Snow depth and snow movement remain among the most important physical limitations. At Carson Spur, up to five of the 16 exploders have the tendency to become buried during the snow year. Additionally, wildfire-related vegetation loss has changed wind loading enough that some units can now get buried earlier in the season than previously. Burial generally becomes a serious operational problem for Caltrans equipment when snow depth reaches around six meters depth at an exploder site (Bickor, 2026). Once an exploder is deeply buried, it is effectively unavailable until conditions allow access to dig out, or the snowpack settles and exposes the nozzle again. Design changes from the manufacturer have helped mitigate this issue, and Caltrans describes how this concern highlights the importance of pre-install planning and local knowledge of the terrain and snowpack. Certain adjustments during the install can allow for some added wiggle room in addressing burial concern, such as raising the concrete foundations to move an exploder higher off the ground. WYDOT has similarly documented snow depth-related limitations to fixed avalanche control infrastructure, emphasizing lower snow depths and improved target coverage when relocating a problematic Avalanche Guard installation (Yount and Gorsage, 2016).

In the 1990’s and early 2000’s, Caltrans moved several exploders shortly after initial installation as crews learned where they performed best, again highlighting the strategic planning required for effective installation, and how important it is to be willing to adapt. Regarding the planning of site locations, Bickor cautions against assigning a simple 'effective range' to any explosive or Remote Avalanche Control System. He has observed a Gazex trigger a slab avalanche more than a quarter mile away while, in other circumstances, failing to move snow only a few feet below the exploder. For operational planning, the critical question is therefore not a fixed radius, but whether the exploder is positioned at a meaningful trigger point and whether terrain features allow the pressure wave to influence the intended snowpack.

Coverage limitations are therefore site specific. Carson Spur contains tight micro-terrain features that can restrict shock-wave propagation and require a relatively dense network of exploders. Carson Pass provides more possible site locations within larger bowls, but deeper snow can compromise otherwise favorable locations. Cornice mitigation is another imperfect application: Gazex may not remove a cornice as completely as would be required above an open ski area slope, but Caltrans has found it effective when removing the more fragile portion is enough to meet highway operational objectives.

These limitations explain why Caltrans continues to maintain backup tools. The Caltrans LoCats remains operational where terrain cannot be adequately covered by fixed RACS or where deep snow buries exploders. The DaisyBell provides additional options during high intensity storms when lower-frequency paths become a concern. Bickor maintains that no RAC System can claim 100% reliability. The operational lesson is therefore not that Gazex must work everywhere, but that every exploder and avalanche path requires a viable backup plan.

Perhaps the central lesson from the Caltrans experience is that RACS should not be viewed simply as an 'easy button.' The technology makes individual mitigation missions easier, but a reliable remote avalanche control program requires long-term investment in infrastructure, skilled personnel, forecasting, strategic planning, preventative maintenance, and a willingness to adapt as field experience reveals weaknesses.

9. FUTURE OF REMOTE AVALANCHE CONTROL AT CALTRANS

Many of Caltrans’ original Gazex installations operated well beyond the service life initially anticipated for the equipment. Most Carson Pass exploders remained in service for roughly 32 years, substantially exceeding the service life originally anticipated for the equipment. Caltrans identified the need for a broad replacement program in 2013 and began replacing units at Carson Spur in 2017. By the end of summer 2026, nearly every exploder and shelter in the statewide system will have been replaced within the previous decade, with five older shelters on Carson Pass planned for replacement in the coming years.

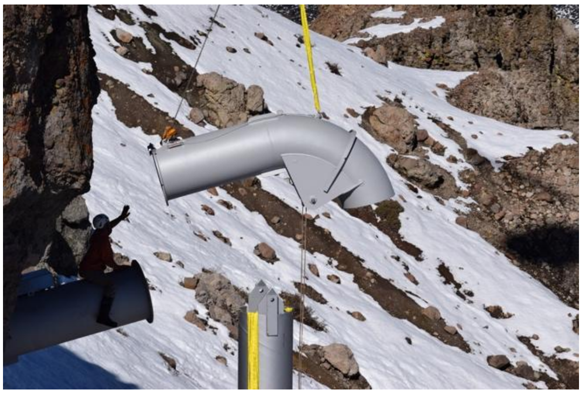

Figure 8: Gazex exploder replacement at Carson Spur, 2021.

At present, Caltrans has no major new RACS installations planned after the 2026 work, although additional RACS remain a possibility. Expansion is not limited primarily by the technology itself; land-use and special-use permitting, particularly where avalanche starting zones lie on U.S. Forest Service land, can delay or complicate projects. If those constraints and funding were removed, Bickor's preference would be for more RACS where they can reduce exposure and closures.

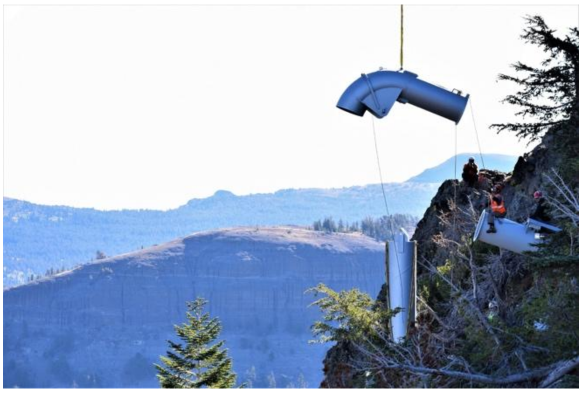

Figure 9: Gazex exploder replacement at Carson Spur, 2022.

The larger uncertainty for Caltrans is the future of backup mitigation. The LoCat remains valuable, but the original manufacturer no longer supports the system and Caltrans has had to develop replacement ammunition. Its long-term viability is therefore uncertain. Bickor considers a backup plan for every individual exploder essential, and one of the program's largest unresolved questions is how to operate if a practical long-range backup system is no longer available.

Remote avalanche control is nevertheless expected to only become a larger part of the Caltrans program. Future improvements will likely combine modernized or expanded RACS with better forecasting, monitoring, communications, and emerging technologies intended to minimize highway closure time and reduce exposure to workers and the traveling public. The Caltrans program has always evolved through field innovation and cooperation among operators, manufacturers, and engineers. Continued communication and a willingness to modify systems rather than dismiss a technology when problems arise will remain critical to that evolution (Bickor, 2026).

10. CONCLUSION

Caltrans' experience with RACS spans more than three decades and several generations of avalanche workers. What began largely as a response to the declining reliability of aging 75 mm military ammunition ultimately changed the operational philosophy of avalanche mitigation on California highways.

Remote avalanche control has allowed Caltrans to conduct mitigation more rapidly, with fewer personnel, and at times when conventional operations would require substantially greater effort and worker exposure. At individual starting zones, fixed exploders have eliminated repeated hour-plus access previously required for hand charging. Improvements in maintenance and program management have increased reported firing reliability to greater than 99%.

History demonstrates that the value of RACS cannot be measured simply by the convenience of remotely firing an exploder. Early experience showed that ease of operation can result in operational challenges from excessive firing and deferred maintenance with a "set it and forget it" mindset. Early design and infrastructure problems reinforced the need to treat RACS as long-term infrastructure rather than seasonal equipment.

RACS also produced organizational effects beyond avalanche missions themselves. In the early years of the program, the Caples maintenance yard closed for roughly six months each year. The maintenance demands of the growing RACS program helped justify year-round positions, providing the dedicated personnel that the original system ultimately required. That staffing change, combined with a stronger maintenance culture, has been central to the improvement in system reliability.

Caltrans reports a dramatic reduction in near misses and close calls since introducing RACS to their operations. Although those observations do not provide a controlled statistical comparison, the operational mechanism is clear: remote systems have removed repeated personnel exposure from many routine control missions and reduced the need to recover unexploded ordnance or access starting zones during severe weather.

After more than 30 years, perhaps the most important lesson from Caltrans is therefore not that remote avalanche control replaced traditional avalanche work, rather, it changed where that work occurs. Personnel exposure and logistical effort during individual mitigation missions can be reduced, while greater emphasis is placed on forecasting, system design, preventative maintenance, planning, and strategic decision-making. That evolution may ultimately represent the most enduring impact of RACS on the Caltrans avalanche program.

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