AVALANCHE WARNING SIGNS ON HIGHWAYS: A PRACTITIONER'S FRAMEWORK FOR DESIGN, PLACEMENT, AND RISK-BASED STANDARDIZATION

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ABSTRACT: This paper examines how transportation agencies design, place and deploy avalanche warning signage, and proposes a framework for standardizing those decisions. Avalanche warning signage is a critical component of risk management for transportation corridors in avalanche-prone regions. Avalanche hazard and risk assessment, and operational risk management on highway corridors are generally mature practices, but the deployment of signage is not. Once an agency knows where its avalanche paths are, it must determine which of them carry signage, what that signage says, where each sign should stand, and which road users it addresses. Neither the *Manual on Uniform Traffic Control Devices* nor the *Vienna Convention on Road Signs and Signals* treats avalanches as a distinct hazard class, so agencies develop signage policy independently.

We reviewed the signage practices of 10 agency programs in the Transportation Avalanche Research Pool, across North America, New Zealand and Norway, and found little consistency in signage deployment between agencies. Much of the variation is a defensible response to context, but the decisions are made in isolation, without reference to peer practice or to the evidence on sign effectiveness, which risks the inconsistent messaging that erodes driver compliance. In response, we propose a framework for agency-level signage manuals spanning deployment thresholds, placement criteria and sign design, supported by maintenance and records. The framework standardizes the basis on which signage decisions are made while allowing for local context.

KEYWORDS: avalanche signage, highway avalanche risk management, transportation infrastructure.

1. INTRODUCTION

Transportation agencies have applied and refined avalanche risk assessment on highway corridors for decades, drawing on a mature set of methods: hazard and path mapping, magnitude-frequency analysis, estimation of exposure and vulnerability, and index-based rating through the Avalanche Hazard Index (AHI; Schaerer, 1989). That assessment informs corridor risk management, in which independent, partially overlapping treatments operate concurrently, so that no single failure exposes the road user to a catastrophic outcome (Reason, 1997). Signage is a component of this operational system. It is intended to reduce the exposure and vulnerability of road users and demonstrate the transportation agency's duty of care. The criteria for deploying signage, however, are less well established, and are not documented or applied consistently across agencies. Once an agency has characterized the risk along a corridor, it must determine which paths and/or areas warrant signage, what that signage says and looks like, where it stands, and whom it addresses.

The *Manual on Uniform Traffic Control Devices* (FHWA, 2009) and the *Vienna Convention on Road Signs and Signals* (UNECE, 1968) prescribe colour, shape and placement conventions for hazard warning and regulatory signage, but neither treats avalanches as a distinct hazard class. Agency construction manuals and internal policies seldom supply the missing criteria, and the avalanche-specific signage literature is sparse. A sign works only if the driver detects it, reads it, understands it, and acts on it (Figure 1). Enforcement of regulatory signage lies outside the transportation authority's jurisdiction, so driver engagement and education are the principal means available to the authority for improving compliance. An effective and defensible program treats signage as a system, in which design, placement, activation thresholds, maintenance, records and enforcement operate together.

This paper addresses that gap. We set out what the behavioural and ergonomic evidence establishes about sign effectiveness, document how avalanche signage is currently deployed across agency programs, and identify where current practice departs from that evidence. From those deficiencies, we advance deployment, placement

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and design recommendations, and set out a practitioner framework that implements them in an agency-level signage manual.



Figure 1: Poor compliance indicates a failure for a driver to detect, read, understand and act on a sign. (Photo credit: Colorado Department of Transportation)

2. BACKGROUND

Avalanche mitigation on highway corridors combines active and passive treatments. Active treatments act on the hazard, or on the timing and duration of exposure, and include explosive avalanche control and traffic management. Passive treatments operate continuously, without human intervention. Avalanche signage is a passive treatment that acts on the road user.

Signage performs two primary functions and one secondary function. It reduces vulnerability by priming the driver to respond to unexpected conditions that may arrive. It reduces the duration of exposure by restricting where vehicles stop within an avalanche path. Secondarily, it communicates the operational state of the corridor, which reduces the disruption avalanche operations impose on the transportation network.

Avalanche signs influence road users through four design variables: (1) placement, (2) shape, (3) colour and (4) pattern, and symbols or text (CIE, 1988), all of which the driver must process within a single glance.

2.1 Sign classification

Road signs on highway corridors divide into three classes of distinct legal standing. Class selection governs both the design treatment the authority applies to a sign and the liability the authority carries when a driver does not comply (Figure 2).

- **Regulatory signs** enforce traffic law, and non-compliance may result in a violation or fine. They subdivide into prohibitory signs, which specify an action a road user must not take, and mandatory signs, which specify one they must.
- **Warning signs** inform drivers of a hazard ahead. They provide cautionary advice only and carry no penalty for non-compliance.
- **Indicative signs** direct actions traffic law does not require, such as marking safe stopping or traffic pooling areas.



Figure 2: (a) BC MoTI regulatory avalanche sign; (b) CDOT avalanche warning sign; (c) MRA indicative safe-stopping-area sign.

2.2 Avalanche-specific signage functions

Avalanche programs deploy five sign types within this classification.

- Avalanche warning signs announce entry into an avalanche-exposed section of road and prime the driver for debris on the running surface and for sudden visibility loss within a powder cloud, neither of which gives advance warning.
- Variable-message signs deliver real-time road-condition updates, so drivers can manage exposure through periods of elevated hazard, active control and closure.
- Regulatory no-stopping and no-parking signs reduce exposure by prohibiting vehicles from stopping within an avalanche hazard area. A stopped vehicle occupies the runout for the duration of the stop; a moving vehicle clears it within seconds.
- Road-closure signs and gates eliminate exposure. Programs may deploy them seasonally, in response to elevated hazard, or during active explosive avalanche control.
- Indicative signs mark safe stopping and parking areas and terminate regulatory re-

strictions. A no-stopping restriction is actionable only where the driver knows where stopping is permitted.

2.3 Methods

This study draws on two instruments. The first is a structured review of the international road sign literature for the behavioural and ergonomic evidence governing sign effectiveness. The second is a review of signage practice across 10 agency programs participating in the Transportation Avalanche Research Pool (TARP) in North America, New Zealand and Norway. In 2024 we surveyed managers, supervisors, forecasters and asset managers from those 10 programs on the importance, effectiveness and road-user comprehension of their signage within their operational context.

2.4 Challenges to signage effectiveness

Signage effectiveness is the degree to which a sign produces the driver response the authority intended: compliance for regulatory signs, and hazard recognition with a corresponding behavioural adjustment for warning and indicative signs. In either case the driver must first detect, read and understand the sign. Respondents rated signage an important component of their avalanche risk mitigation system, and rated both its effectiveness and road-user comprehension well below its importance (Figure 3).

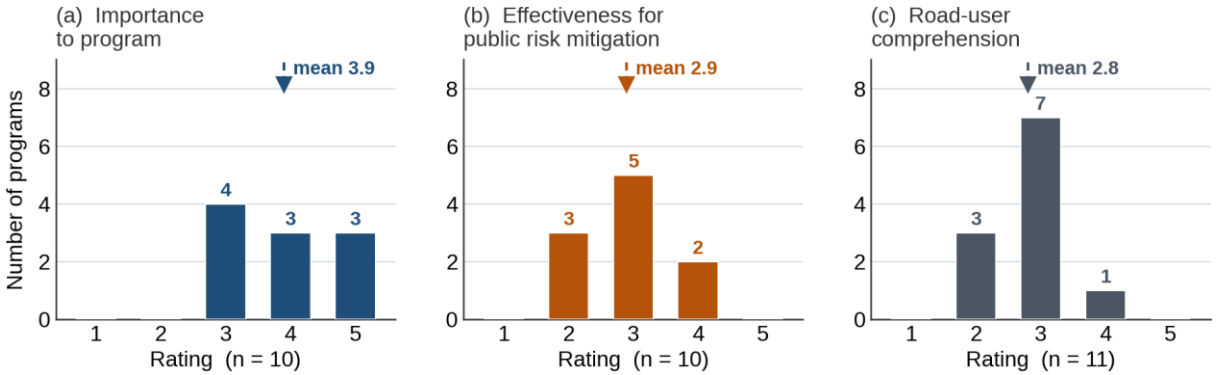


Figure 3: survey ratings of signage importance, effectiveness for public risk mitigation, and road-user comprehension across participating programs. (Importance scale: 1 = not important ; 5 = very important)

Because no common framework exists, agencies develop their signage policies independently. Sign fatigue erodes attention where signage is excessive, and authorities carry legal liability for signage deployed without a defensible basis, or for signage specifying an action they do not enforce (Slop, 1995).

Operating conditions compound these difficulties. Periods of elevated hazard coincide with the storm conditions that most degrade sign visibility, snow buries signs, and retroreflective surfaces degrade with weathering. Road users vary in their familiarity with the hazard and the local language, and that variation is greatest on tourist and long-haul freight corridors.

Enforcement constrains effectiveness further. Regulatory signage carries legal force only where a traffic authority enforces it, and traffic authorities rarely patrol avalanche corridors during the conditions that make the restriction necessary. A sign enforceable in principle but unenforced in practice delivers only the compliance of a warning sign while carrying the liability of a regulatory instrument.

The survey found signage use inconsistent between agencies, and in some cases within a single agency. Programs differ in which paths receive signage, which sign classes apply and where they place signs relative to path boundaries. Design conventions are more uniform than deployment policy, because both frameworks set colour and shape while leaving the remaining decisions to each agency. Few programs hold a governing signage policy or defined criteria for when and where signage is required.

Much of this variation is defensible. Programs operate across different contexts ranging from single tourist corridors to national networks, and from corridors where closure carries severe economic consequence to those where the agency accepts seasonal closure. Examined individually, most decisions are reasonable: a program that prohibits stopping throughout a corridor has little need to delineate individual paths. But agencies do not use common criteria. Compliance degrades where a directive is ambiguous or where agencies apply it inconsistently (Wogalter et al., 2002), and where signage differs in class, wording and placement between corridors, drivers cannot transfer learned meaning from one corridor to the next.

Respondents consider signage important but have little confidence in its effectiveness. A

framework grounded in the evidence on road-sign effectiveness would address that gap.

2.5 Standardized principles and the role of context

No single signage convention suits every corridor. Strategy must respond to geographic scale, traffic volume and composition, avalanche frequency and magnitude, route alternatives, and the economic consequence of closure. For example, a threshold or placement rule suited to a high-volume primary highway through mitigated terrain does not suit a low-volume tourist corridor crossing dense avalanche terrain.

Context does not argue against standardization. The principles governing sign design and placement are common to all corridors: sign class follows legal standing, conspicuity and legibility derive from established ergonomic criteria, and agencies must apply thresholds consistently wherever drivers meet the same signage repeatedly. Context changes the value each agency assigns to those parameters.

3. PRINCIPLES OF EFFECTIVE SIGNAGE DESIGN

Avalanche signage is a specialized application of road signage, and almost no research addresses it directly. The evidence governing sign effectiveness derives instead from the wider road sign literature. Researchers developed that literature on general road networks, under conditions that rarely include darkness, blowing snow, and rapid visibility loss characteristic of avalanche terrain. Practitioners should therefore treat its quantified thresholds as upper bounds, rather than as values validated for winter mountain corridors. That literature also measures response to individual signs and offers little on how a sign performs within a mitigation system.

This review applies two principles:

1. **Signage is cumulative**: signs function as a connected set, so what a driver has already passed shapes the response to the next sign.
2. **Signage is also sequential**: effectiveness depends on a chain of driver responses, and each must succeed for the next to be possible.

3.1 Priming

Priming is the effect by which one stimulus shapes the response to a later one, without the driver consciously connecting the two. Applied to signage, what a driver has already passed conditions how quickly and accurately they interpret the next sign. Priming is consequential in avalanche terrain, because the conditions a sign announces arrive without notice and the driver can only prepare for them in advance. Two mechanisms produce the effect. Semantic priming occurs where one sign prepares the driver for an upcoming condition (e.g. an avalanche warning sign primes the driver to watch for avalanche indicators). Repetition priming is automatic and unconscious, so a warning sign at the start of a corridor supports recognition of a no-stopping sign on entry to an avalanche area (Crundall and Underwood, 2001; Castro and Horberry, 2004; Koyuncu and Amado, 2008).

Overuse of hazard warning signs diminishes their effectiveness (sign fatigue) and causes drivers to underestimate risk (Jørgensen and Wentzel-Larsen, 1999; Wogalter et al., 2002). Signage must therefore be dense enough to exploit repetition priming but not so dense that sign fatigue erodes the effect. Agencies therefore need an accurate risk assessment before they can design or place signs.

3.2 A four-stage framework

Lay (1998) frames signage effectiveness as four sequential stages, each of which the driver must pass within a single glance: (1) detect the sign (conspicuity), (2) read it (legibility), (3) understand it (comprehension), and (4) act on it (compliance). Failure at any stage voids those that follow. An authority that designs to these stages matches the sign to the perceptual and cognitive limits of the driver on the road (Ben-Bassat and Shinar, 2006; Ishartomo et al., 2020).

Conspicuity determines whether the driver detects the sign. It improves with visual angle, edge contrast and border width, and with colour that is both high in contrast and high in luminance. Retroreflective materials, illumination and flashing beacons extend detection into darkness and low visibility, and faded or damaged signs are less conspicuous than maintained signs. A sign must fall within 8–10 degrees of the driver's line of sight for the driver to detect it in a single glance, and detection is reduced during periods of precipitation (Castro and Horberry, 2004; Rousseau and Wogalter, 2006; Babić et al., 2022).

Legibility determines whether the driver can read the sign at a given distance in the time available. Required letter height depends on vehicle speed, message length, and the distance at which the sign must first be readable (Castro and Horberry, 2004). Faster corridors and longer messages demand larger signs placed further in advance; typical legibility distances in good light range from 60 m for fine detail to 250 m for symbols and illuminated signs. Glance constraints limit message

length. Each post should carry only one sign of a given type, and although more signs convey more information, displaying more than three at once reduces how much of it the driver comprehends (Kwon et al., 2024).

Comprehension determines whether the driver interprets the message correctly. A message must be meaningful, unambiguous, and detailed but short, and the sign must distinguish mandatory from prohibitory instructions (Castro and Horberry, 2004; Dewar and Pronin, 2023). Shape and colour carry hazard level independently of text. Drivers rank warning-sign shapes from the inverted triangle at the highest hazard level to the rectangle at the lowest (Table 1), and the MUTCD and the Vienna Convention establish colour conventions (Zhu et al., 2020) that aid comprehension. Pictorials assist non-readers and non-native speakers and can be used with or without text (Dewar, 1988).

Table 1: Warning-sign shape–hazard hierarchy.

Shape	***Hazard Association and Usage***
	Highest hazard level. Drivers recognize it quickly as a warning of significant danger.
	Second in the hierarchy. Signals a high hazard level, below the inverted triangle.
	Third in the hierarchy. Indicates a lower hazard level than either triangle.
	Fourth in the hierarchy. Marks warnings that do not imply immediate or severe danger.
	Lowest hazard level. Used for informational signs rather than warnings.

Compliance is both a cognitive and a physical response. Cognitively, the driver must judge the message credible and the required action appropriate; relevance depends on whether the driver must act and whether preceding signs proved useful (Castro and Horberry, 2004). High cognitive load reduces compliance (Lyu et al., 2017). Compliance with regulatory signs depends on consistent enforcement, and warning signs perform best where they state the consequence of non-compliance (Wogalter et al., 2002). Physically, the driver must respond to the message with appropriate behaviour, which requires the sign to stand far enough in advance of the hazard area.

4. RECOMMENDATIONS

Operational contexts and regulatory regimes vary too widely for prescriptive sector-wide standards. Agencies should develop their own signage policies, taking account of corridor conditions, existing signage practices, and established signage principles. The framework spans five domains, applied in sequence: deployment thresholds, placement criteria, sign design, maintenance and records, and policy. These are summarized in the following subsections.

Three established principles underpin the recommendations that follow:

- Signage decisions should rely on risk assessments that define path boundaries and hazard thresholds (e.g., avalanche magnitude and frequency, avalanche hazard index).
- Design and placement standards should satisfy the four ergonomic stages.
- Signage should exploit the benefits of priming without the overuse that diminishes effectiveness.

4.1 Deployment thresholds

Deployment thresholds are determined by the risk conditions under which an agency operates. This includes:

- Establish agency standards for minimum risk thresholds that identify which paths and areas need signage, expressed as AHI, magnitude-frequency or return period, and apply them consistently across the jurisdiction. Consistency between jurisdictions is neither achievable nor necessary; consistency within one supports repetition priming. Where corridors cross jurisdictional boundaries, however, adjacent agencies should coordinate their signage so that drivers meet a consistent message along a continuous route.
- Assign thresholds by sign class. Warning signs warrant a lower threshold than regulatory signs, because a warning sign imposes no compliance burden on the driver and no enforcement burden on the agency.
- Treat thresholds as minimum requirements. Adopt a more conservative threshold where exposure or vulnerability is elevated, such as a scenic lookout where drivers stop and leave their vehicles, or where closure carries severe economic cost. At such locations driver behaviour, not avalanche frequency and magnitude, sets the exposure.

- Remove or cover avalanche signage outside the avalanche season. Seasonal treatment keeps warnings credible, reinforces salience during periods of hazard and reduces visual clutter.

4.2 Placement criteria

Placement criteria specify a sign's location relative to the avalanche path and approaching drivers. This includes:

- Sign every avalanche area meeting the threshold with a warning sign. The warning sign reduces vulnerability to unexpected conditions and semantically primes the driver to recognize and comply with any regulatory signage that follows.
- Bracket individual paths, or groups of adjacent paths, according to the spacing between them. Grouping avoids repeated start-and-end pairs that increase cognitive load without conveying information.
- Mirror regulatory signs with an end-of-restriction indicative sign.
- Sign safe stopping areas explicitly with indicative signage, rather than by an unsigned break between avalanche areas. An absent sign carries no message, and the driver cannot distinguish a safe gap from an unsigned hazard.
- Determine placement in consultation with traffic engineers. The avalanche specialist defines the hazard boundary; the traffic engineer determines how the sign should be integrated into the road environment, considering sight distance, geometry, speed, intersection proximity, and year-round visibility.

4.3 Sign design criteria

Sign design criteria specify the form of the sign and its message. This includes:

- Commission a standard avalanche warning icon for adoption into the MUTCD and the Vienna Convention. No program surveyed uses a distinct avalanche symbol or shape, and a shared icon is the one deficiency a sector-level action can close directly.
- Match sign class to form (Table 2).
- Tie sign dimensions to traffic speed. Required letter height rises with vehicle speed and message length. The MUTCD specifies standard sizes; adopt larger sizes where speed, sight distance or visibility warrant.
- Specify retroreflective material, with illumination where low light warrants it.
- Define standardized message libraries for variable-message signs, which communications personnel without avalanche expertise commonly operate.

4.4 Maintenance and records

Maintenance keeps signs functional and records document their condition, location and compliance over time. This includes:

- Inspect signs annually for damage, fading and obstruction by snow, vegetation or debris. Before winter, address faded retroreflective surfaces and structural wear, since faded colour and damaged symbols reduce conspicuity.
- Specify sign profiles that shed snow. Clear snow around signs. Signs are least visible during the storms that generate the hazard they mark.

Table 2: Class-specific design rules. MUTCD and Vienna Convention forms.

Sign Class	***MUTCD form***	***Vienna Convention form***	***Auxiliary treatment***
Warning	Diamond, yellow; fluorescent yellow-green where extra attention is warranted	Triangular, often incorporating an exclamation mark	Auxiliary text specifying the hazard (e.g. AVALANCHE AREA NEXT 15 km). Must not direct behaviour; behaviour-direction is reserved for regulatory signs.
Regulatory	Red circle with slash or cross; some with white background and black or red elements	Red circle with slash or cross	Auxiliary text. Pair with an end-of-prohibition sign rather than a distance indicator: END OF NO STOPPING AREA, not NO STOPPING NEXT 15 km.
Indicative	Green legend and border on a white background	A square or rectangular sign featuring a blue background with a white letter	Terminates prohibitions and guides drivers to safe stopping or parking areas.

- Maintain a record for each sign covering location, installation date, condition, maintenance history and standards compliance. Hold records in a geographic information system, since the agency cannot audit coverage against a path inventory unless sign records are spatially referenced.

4.5 Policy

Policy records the agency's standards in a signage manual and situates them within its legal and operational context. This includes documenting the framework in an agency-level signage manual and specifying:

- **Operational context**. Traffic patterns, avalanche frequency and magnitude, road users, operational risk tolerance and expectations for enforcing regulatory signs.
- **Sign inventory**. Sign types and their intended risk treatment, with a graphical sign index, size specifications and standardized messaging for variable-message signs.
- Placement criteria. Thresholds derived from avalanche risk assessment, visibility standards and road features including curves, grades, sightlines, speeds and traffic volumes.
- **Maintenance and inspection**. Schedules and procedures for inspection, maintenance, replacement and decommissioning, with provisions for year-round functionality and for the non-avalanche season.
- **Record keeping**. Protocols for documenting sign location, type and condition, and a tracking system for installations, replacements and removals.
- **Legal framework and enforcement**. The regulations, policies and legal jurisdictions governing avalanche signage.

Manual sections should cross-reference existing agency documents, including the avalanche safety plan and the agency's traffic control manual.

5. LIMITATIONS AND FUTURE WORK

Agencies of different sizes can adopt the framework because it standardizes the process they follow rather than the decisions they reach. The requirement to establish threshold-setting, placement criteria, inventory, maintenance, and legal framework is common to all agencies; but each agency needs to calibrate these policy elements to local context.

5.1 Limitations

This study has three limitations.

- **Validation**. We have not field-tested the recommendations or validated them for driver comprehension, compliance or incident reduction. Validation would require the comprehension testing and quality standards prescribed by Ishartomo et al. (2020) and Berrio et al. (2023).
- **Transferability**. The analysis is confined to TARP member agencies, which limits geographic and operational transferability.
- **Subjectivity**. The survey results are based on the subjective assessments of program personnel rather than measured outcomes.

The recommendations complement the MUTCD, the Vienna Convention, and local guidelines, and they do not displace the traffic engineer's role in sign placement. This work does not address the adaptation of avalanche signage to in-vehicle displays, advanced driver assistance systems or automated driving.

5.2 Future research

Three research directions follow from the deficiencies this review identifies:

- **Threshold research**. Determine jurisdiction-level hazard or risk thresholds, expressed as AHI or magnitude-frequency, that define where signage is and is not required. Correlating signage characteristics with incident frequency and quantifying the economic impact of closures would give agencies a defensible basis for setting thresholds.
- **Effectiveness validation**. Test signage against performance standards at each of the conspicuity, legibility, comprehension and compliance stages, using comprehension tests, questionnaires and comparative studies. No program surveyed has validated its signage against driver behaviour, so credible design and threshold recommendations will require this validation.
- **Machine vision and automated driving**. Developers train detection algorithms on standard sign designs, so automated systems are least likely to recognize agency-specific designs. Research should establish the sign designs, spatial records and maintenance standards that machine vision requires, and the integration of avalanche messaging with in-vehicle displays.

6. CONCLUSION

Respondents across the 10 programs surveyed rate avalanche signage as an important component of their risk mitigation systems, while rating its effectiveness and road-user comprehension

well below its importance. Signage practice varies widely between agencies, and much of that variation is a defensible response to context. The difficulty is that agencies and even jurisdictions make those decisions in isolation, without a common basis, and drivers learn to disregard inconsistent signage.

The framework proposed here standardizes how agencies make signage decisions rather than what those decisions are. Evidence from roadsign research informs the proposed thresholds, placement criteria, and design principles with parameter values calibrated locally and recorded in an agency-level signage manual. Consistent signage lets drivers transfer learned meaning from one corridor to the next, which is the mechanism by which comprehension and compliance improve.

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