STATEWIDE AVALANCHE HAZARD MODELING ALONG ALASKA'S TRANSPORTATION CORRIDORS

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ABSTRACT: Alaska's road and rail network traverses some of the most active and least observed avalanche terrain in North America, creating persistent challenges for infrastructure resilience and public safety. Avalanche risk assessment for remote transportation corridors is often hindered by a lack of weather, snowpack, and historic avalanche data. This shortage of information makes it difficult to systematically evaluate safety along these routes. We present a statewide avalanche hazard assessment for road corridors in Alaska, utilizing an automated large-scale indication modelling approach. Originally developed in Switzerland, this methodology was implemented via RAMMS::Avalanche and specifically adapted for snow climates in Alaska. The workflow automates the identification of potential release areas (PRAs) to facilitate the simulation of regional-scale avalanche ensembles across Alaska's complex terrain. To address observational gaps, spatially distributed snow input parameters are derived from downscaled climate reanalysis, enabling consistent representation of release conditions across Alaska's diverse climatic regions. Simulations resolve runout extent, maximum velocity, maximum impact pressure, maximum flow height, and deposition for estimated frequent (~30-year) and rare (~300-year) return period scenarios. This large-scale modeling framework enables physically based hazard characterization in data-sparse environments where traditional observation-driven approaches are not feasible. Initial findings indicate significant regional variance in hazard levels, identifying localized clusters of high intensity, or 'hotspots', traversing the road corridors. Comparisons between return periods indicate non-linear increases in runout and impact pressure, with implications for infrastructure exposure and risk management. The resulting dataset provides a standardized, quantitative basis for prioritizing mitigation and supporting operational decision-making for the State of Alaska. More broadly, this work demonstrates a scalable approach for integrating climate-informed snow inputs with large-area avalanche dynamics modeling in high-latitude, observation-limited regions.

KEYWORDS: Avalanche modeling, Transportation corridors, Alaska, Hazard indication mapping, Climate reanalysis.

1. INTRODUCTION

Snow avalanches represent a primary yet poorly characterized geohazard in Alaska, where vast road networks traverse some of the most active and least observed alpine terrain in North America. The state's road and rail infrastructure, critical for supply chains, commerce, and public safety, encompasses thousands of kilometers of steep, glacially carved corridors subject to diverse snow climates ranging from maritime coastal zones to continental interiors. Despite the frequency of high-magnitude events, systematic hazard characterization is severely restricted by extreme data scarcity; much of the state lacks the dense network of weather stations and multi-decadal historical avalanche event databases required for traditional hazard mapping.

Historically, agencies like the Alaska Department of Transportation and Public Facilities (DOT&PF) have managed risk through active forecasting and the Avalanche Hazard Index (AHI; Hamre et al., 2023). AHI is a standardized numerical expression of risk based on the statistical likelihood and severity of vehicles interacting with avalanches. Recent statewide applications in Alaska re-engineered AHI parameters using a "Consultants' Best Estimate" (CBE) method to account for modern traffic volumes and socio-economic loss values (Hamre et al., 2023). Despite the high value of the AHI, it remains inherently retrospective and path-specific, offering limited predictive utility in remote or potential future corridors where historical records are non-existent or in a rapidly changing Arctic and sub-Arctic climate where historical frequency may no longer be a valid proxy

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for future risk.

To classify terrain exposure for mobile elements at risk, practitioners and researchers often utilize the Avalanche Terrain Exposure Scale (ATES) (Statham et al., 2006; Statham and Campbell, 2025). While ATES is a cornerstone of backcountry safety and has been mapped over large areas via automated geospatial modeling (autoATES) (Sykes et al., 2024; Toft et al., 2024a), it remains a static, terrain-based classification tool. ATES identifies susceptible terrain exposure but does not model the physical dynamics of avalanche flow (i.e., maximum velocity, pressure, and flow height) under specific meteorological scenarios.

To address these limitations in Alaska, we focus on large-scale hazard indication mapping (LSHIM). Originally developed in Switzerland, this methodology utilizes high-resolution digital elevation models (DEMs) and Object-Based Image Analysis (OBIA) to identify potential release areas (PRAs) across entire regions (Bühler et al., 2018; Bühler et al., 2022). While traditional hazard maps cover only a small fraction of alpine areas due to high costs, LSHIM provides a spatially continuous overview of hazard susceptibility, resolving runout extent, flow height, velocity, and impact pressure. This approach has been successfully validated at statewide scales in the Swiss Alps and is now being adapted for data-sparse, high-latitude environments.

This study utilizes a hybrid framework, linking climate reanalysis with RAMMS::LSHIM avalanche modeling (Fischer et al. 2026). To overcome the lack of in-situ observations, we derive snow input parameters from downscaled climate model output, enabling consistent representation of release conditions across diverse climatic regions. This allows for the simulation of millions of individual avalanches for both frequent (~30-year) and rare (~300-year) return periods. By quantifying physical hazard intensity metrics (e.g. pressure and velocity) rather than relying solely on static terrain indices, this work provides a standardized, objective baseline for prioritizing mitigation investments, such as Remote Avalanche Control Systems (RACS) and informing long-term infrastructure resilience in a changing climate.

2. METHODOLOGY

The modeling framework follows an approach designed to overcome Alaska's lack of in-situ observations by utilizing three primary data components: high-resolution elevation data, land cover (forest) masks, and downscaled climate model snow data (Fischer et al. 2026).

2.1 Digital Elevation Model (DEM) and Terrain Analysis

The foundation of the study is 5-meter resolution interferometric synthetic aperture radar (IFSAR) digital elevation data. These data are resampled to 10 meters to accommodate the smoothing effect of snow on terrain and to optimize computational efficiency for large-scale simulations. Derived terrain parameters, including slope angle, aspect, plan curvature, ruggedness, and fold, are used to delineate potential release areas (PRAs).

2.2 Potential Release Area (PRA) Delineation

PRAs are identified using an Object-Based Image Analysis (OBIA) approach. This method (Bühler et al. 2013 & 2018) segments the terrain into homogeneous objects based on terrain characteristics, excluding areas where avalanches are unlikely to release, such as slopes flatter than 28° or extremely rugged rock faces. This study separately calculates PRAs for frequent (~30-year) and rare (~300-year) scenarios, with the rare scenario generally allowing for larger, more connected release zones.

2.3 Climate-Informed Snow Inputs

To address the critical lack of meteorological stations, release depths (d0) are derived from dynamically downscaled Climate Forecast System Reanalysis (CFSR) for the period 1981-2010 for Southeast Alaska and European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5) for the period 1940-2024 for southcentral Alaska. To better capture maritime and orographic influences, a spatially variable lapse rate is applied to the downscaled data, ensuring that release conditions are representative of Alaska’s diverse sub-Arctic climates.

To estimate maximum release depths, we applied Extreme Value Theory (Jenkinson, 1955; Coles et al., 2001) to the daily WRF output. Daily snowfall was aggregated into 3-day intervals (Δt=3 days) to construct a time series, from which annual maxima were extracted for each year (July–June). These annual 3-day maxima were fitted to a Generalized Extreme Value (GEV) distribution using the SciKit-Extreme Python package and sampled to derive maximum 3-day snowfall totals for 30 and 300-year return intervals.

2.4 Numerical Simulations

To facilitate the simulation of regional avalanche ensembles, this study utilizes RAMMS::LSHIM (Large-Scale Hazard Indication Mapping), a module of the RAMMS::Avalanche software (Christen et al. 2010) specifically designed for the regional execution of numerical simulations (Bühler et al., 2022). The model solves depth-averaged mass and momentum equations governing two-dimensional flow across three-dimensional terrain and frictional resistance is calculated using the two-parameter Voellmy relation. For high-latitude applications in Alaska, the model incorporates spatially distributed climate model-derived snow input and automated PRAs to characterize potential flow behavior across diverse climatic zones.

2.4.1 Parameterization and Volume Classification

The modeling workflow automatically assigns friction parameters based on avalanche release volume, which is calculated as the product of the PRA area and the release depth perpendicular to the slope. Following the standard Swiss modeling protocol, PRAs are categorized into four volume classes: Tiny (<5,000 m^3), Small (5,000-25,000 m^3), Medium (25,000-60,000 m^3), and Large (>60,000 m^3) (Bühler et al., 2022). These categories guide the selection of Voellmy friction parameters, friction (μ) and turbulent resistance (ξ), with larger avalanches generally receiving lower friction values to account for increased mobility (Christen et al. 2010).

2.4.2 Forest Interaction

The model integrates a land cover mask to simulate the dual role of forests in avalanche mitigation (Bebi et al., 2021). Forests are assumed to suppress release within the PRA delineation stage. During the runout phase, the interaction is determined by avalanche magnitude (Bühler et al., 2022):

- Braking Effect: For Small and Tiny avalanches, the turbulent friction is set to simulate vegetation-induced deceleration.
- Forest Destruction: For Medium and Large avalanches, the protective effect is neglected under the assumption that the high impact pressures will destroy the forest stand without providing significant braking.

2.4.3 Computational Domain and Efficiency

To manage the extreme scale of Alaska's corridors, the workflow employs an automated Domain Builder. Rather than calculating across a continuous statewide grid, the system generates unique, rectangular compute domains for every individual PRA. This domain is sized based on a minimum area bounding rectangle (MBR) that encompasses the PRA and all downslope grid cells, with an additional buffer added to ensure all possible runout is captured. This process allows the model to process millions of independent simulations in sequence across high-performance Linux clusters.

2.4.4 Post-Processing and Hazard Outlines

Raw simulation outputs resolve maximum flow height, velocity, and impact pressure per calculation cell (Bühler et al., 2022). To facilitate operational use by the State of Alaska, these rasters are converted into vectorized extent outlines. Outlines are generated using a conservative threshold that includes grid cells with a flow depth and a velocity (Bühler et al., 2022). This provides a standardized, quantitative hazard footprint that can be directly compared against existing site-specific assessments.

While this framework provides a scalable approach for automated potential release area (PRA) delineation, volume estimation, and dynamic flow simulation across Alaska, its outputs are constrained by input uncertainties and model assumptions (Bühler et al., 2022; Fischer et al., 2026). Primary limitations stem from a sparse meteorological network and the lack of a comprehensive regional avalanche incident database, which prohibit local model calibration and direct validation of modeled release scenarios or return periods. Furthermore, computational terrain smoothing (10 m DEM), land-cover classification errors, and deterministic PRA release assumptions simplify real-world variability. Dynamically, the RAMMS::LSHIM model simulates only dry dense-flow avalanches, omitting temperature changes and powder/wet-snow regimes, entrainment, vegetation/structural interactions, and alternative triggers like cornice collapse or seismic activity. Consequently, these hazard indication maps should be interpreted as broad-scale susceptibility guides rather than site-specific engineering assessments, offering vital initial insights for data-sparse regions where traditional assessments are infeasible.

3. RESULTS & DISCUSSION

3.1 Statewide Spatial Exposure and Return Period Dynamics

Automated physics-based avalanche modeling across Alaska’s road network establishes the first-ever standardized, statewide baseline dataset of snow avalanche interaction with public roads. Historically, vast stretches of Alaska’s highway infrastructure, particularly secondary routes, unmonitored state highways, and industrial corridors, have operated without a quantitative avalanche hazard assessment. By applying a unified, physics-based modeling framework to

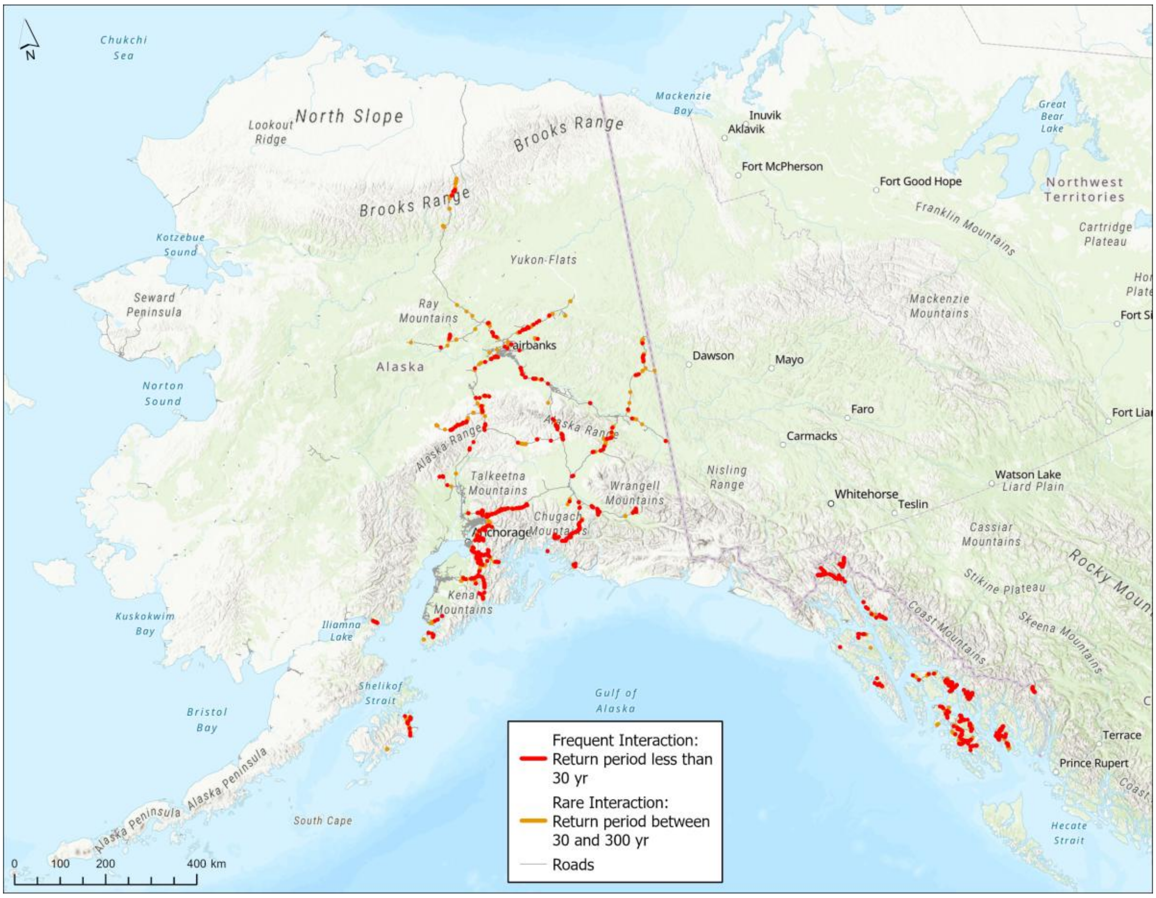

Figure 1: Modeled snow avalanche runout zones affecting Alaskan road networks, corresponding to estimated return periods of 30 and 300 years.

all road corridors in Alaska, this study systematically eliminates these "data deserts" and generates hazard indication maps that create an objective baseline across 2,086 road interaction segments evaluated at 30-year ($T = 30$ yr) and 300-year ($T = 300$ yr) return periods (Figure 1).

Statewide, individual release zones account for 5,376 discrete avalanche paths under 30-year return periods and 6,675 discrete avalanche paths under 300-year return periods. However, when evaluating road impact frequency, it is critical to recognize that while thousands of distinct avalanches initiate from separate high-elevation start zones, many of these slides converge or merge into common avalanche tracks and runout channels before reaching the valley floor. Consequently, multiple start-zone failures frequently coalesce into a single, high-volume impact footprint along the road corridor (Figure 2).

To contextualize these hazard footprints against Alaska's road network, the cumulative avalanche-affected road length expands from 317.5 km under 30-year return events to 625.9 km under 300-year return events (Figure 3). Compared to the 28,324 km of total public road centerlines statewide, avalanche hazards directly affect 1.12% of all public roads at 30-year intervals, expanding to 2.21% during 300-year events.

When evaluated strictly against the 9,045 km primary State Highway System, direct exposure increases to 3.51% (317.5 km) during 30-year events and 6.92% (625.9 km) during 300-year events. Within the 2,943.8 km of high-relief mountain corridors surveyed in this study, avalanche interactions affect 10.79% of corridor length at 30-year return intervals, nearly doubling to 21.26% under 300-year return intervals.

3.2 Regional Hazard Profiles and Vulnerability Across Road Classifications

Southcentral and Southeast Alaska exhibit distinct regional avalanche risk profiles (Figure 3). Southeast Alaska exhibits higher hazard intensity during frequent 30-year events, recording a mean impact pressure of 57.6 kPa (2.44 times higher than Southcentral's 23.6 kPa), higher flow velocities (9.55 m/s vs. 6.86 m/s), nearly double the mean flow height (1.98 m vs. 1.05 m), and deeper average debris deposits (1.44 m vs. 0.83 m). The steep fjord topography in Southeast Alaska routes maritime avalanches directly onto narrow coastal highways over short runout distances.

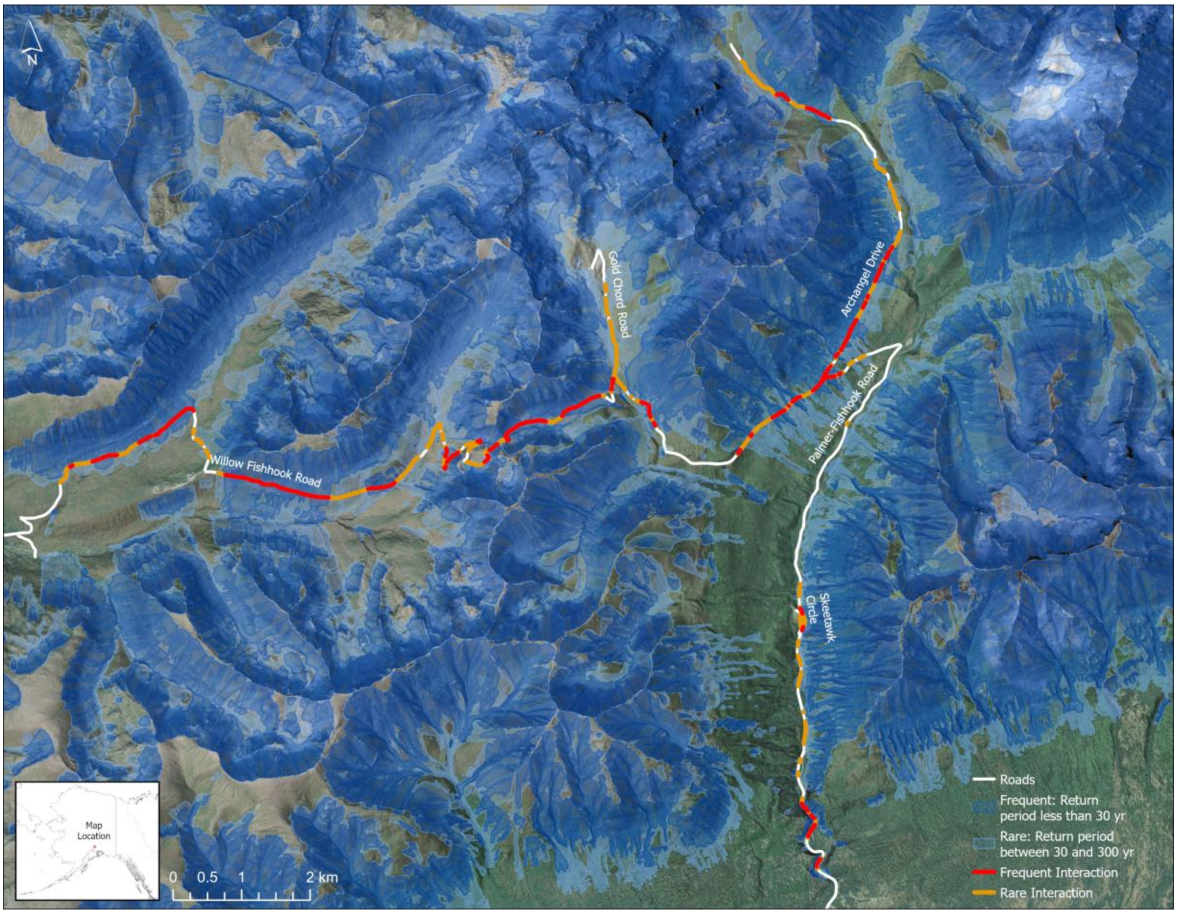

Figure 3: Modeled 30-year and 300-year snow avalanche runouts in the Hatcher Pass area along Palmer-Fishhook and Willow-Fishhook roads in the Talkeetna Mountains, Alaska. Colored line segments highlight road locations exposed to avalanche events at each return period.

Conversely, Southcentral Alaska exhibits massive spatial footprint expansion during rare events (Figure 1). Southcentral's avalanche-affected road length expands by 182.0% (from 137.1 km across 2,905 avalanche paths to 386.6 km across 4,829 paths) between 30-year and 300-year return periods. Broad mountain pass corridors in Southcentral (e.g., Turnagain Arm and Thompson Pass) feature large starting zones where synoptic 300-year storms trigger low-frequency, long-runout avalanches that inundate extensive road segments.

Evaluating these dynamic outputs across AK-DOT&PF road classifications highlights vulnerability trade-offs (Figure 4). Arterial roadways face the highest impact pressures, averaging 68.0 kPa at 30-year intervals and 111.2 kPa at 300-year intervals. Threshold analysis reveals that 38.3% of all avalanche-affected segments state-wide breach 30 kPa (commonly associated with destruction of wood-frame structures; McClung and Schaerer, 1993), while 19.0% breach 100 kPa. During 300-year events in Southeast Alaska, 10.3% of segments breach 250 kPa.

<u>*3.3 Debris Deposition Depths and Corridor Hotspots*</u>

Debris deposition depth determines clearing equipment requirements, road closure durations, and operational hazard exposure. Statewide, mean maximum deposition depth increases from 1.12 m under 30-year events to 1.46 m under 300-year events (Figure 5). On high-speed Arterial corridors, mean deposition depths reach 1.69

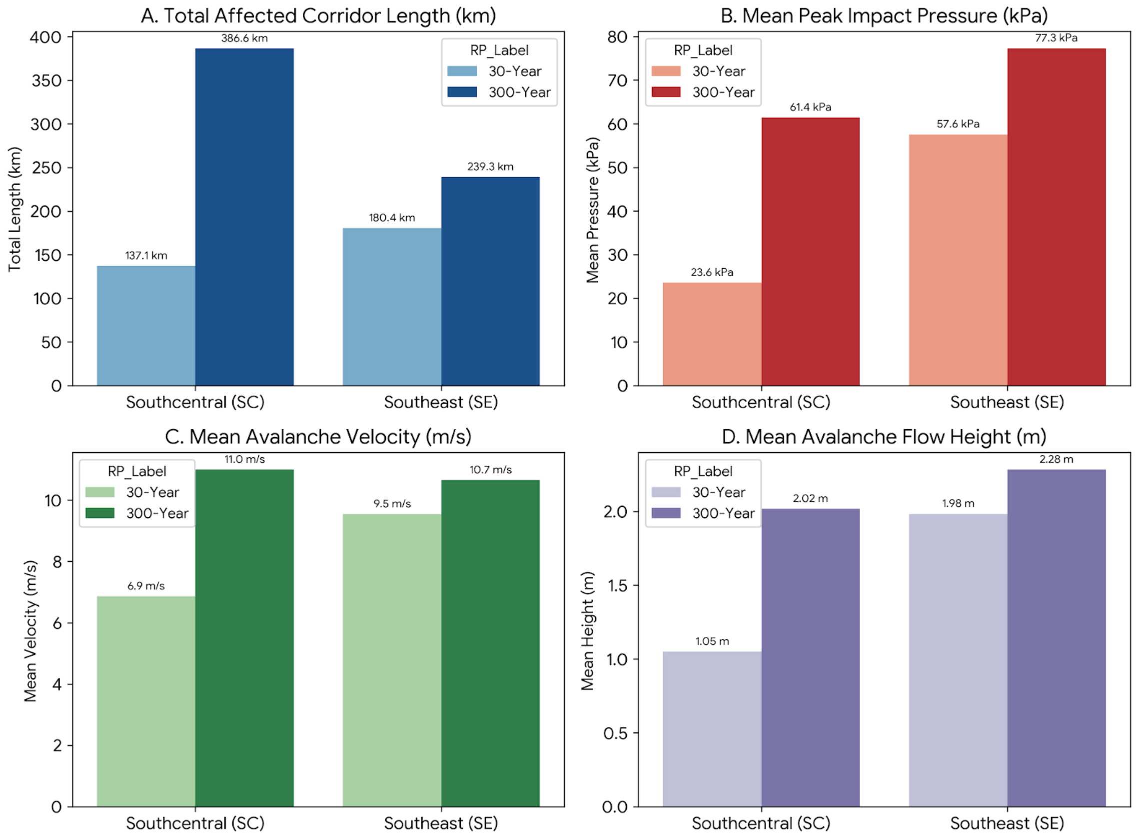

Figure 4: Regional and return period breakdown of avalanche interaction metrics across Alaska transportation corridors. (A) Total affected road corridor length in kilometers across Southcentral (SC) and Southeast (SE) Alaska. (B) Mean maximum impact pressure in kilopascals. (C) Mean flow velocity in meters per second. (D) Mean flow height in meters. All panels compare 30-year (light shade) and 300-year (dark shade) estimated return periods.

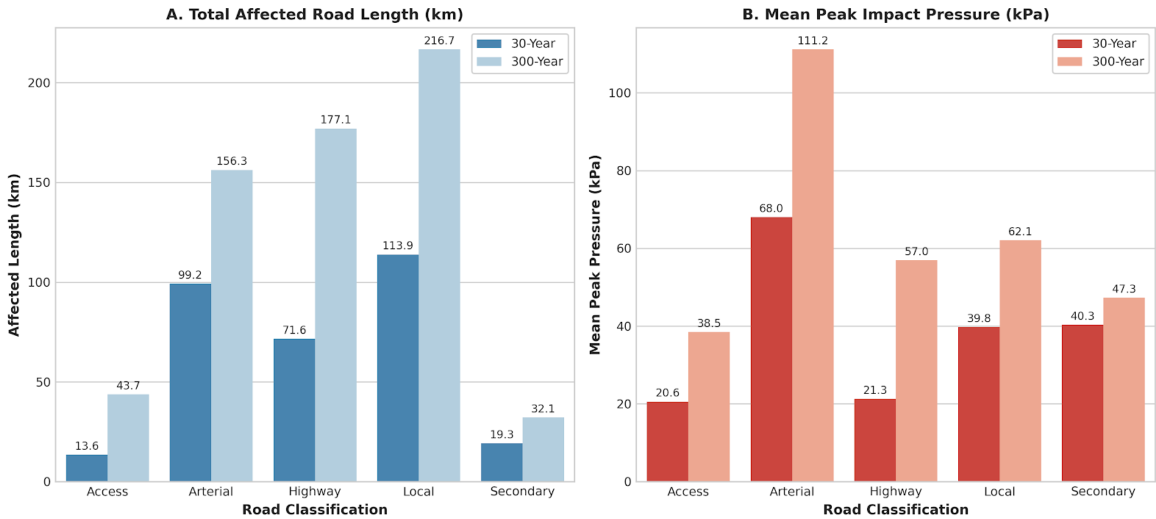

Figure 5: Impact metrics classified by roadway functional type. (A) Total affected roadway length in kilometers across Access, Arterial, Highway, Local, and Secondary roads. (B) Mean peak impact pressure in kilopascals per road category under 30-year and 300-year return events. Arterial roadways exhibit the highest impact pressures, while Local and Highway classifications account for the greatest total length of exposed infrastructure.

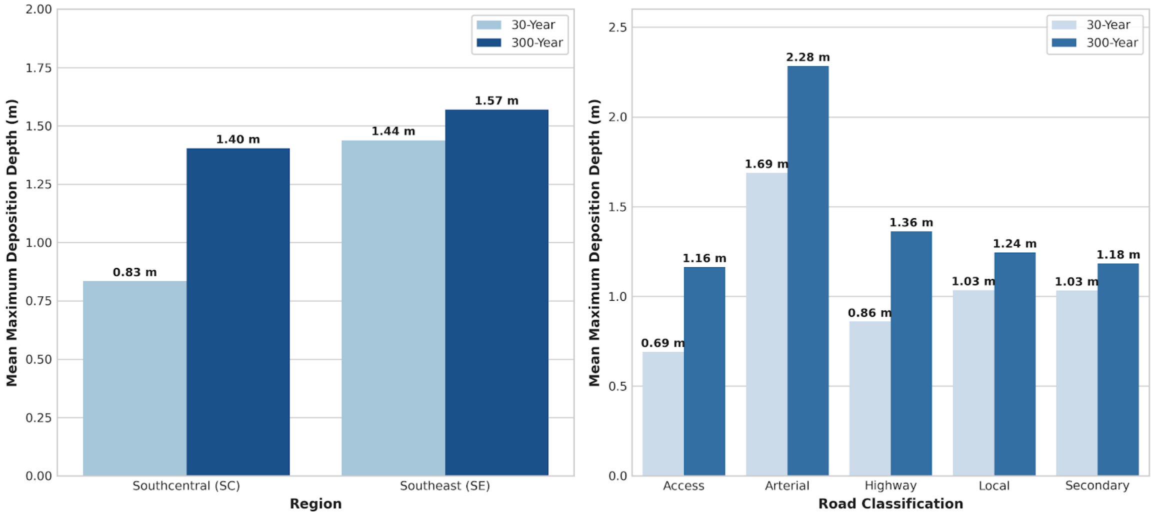

Figure 5: Maximum avalanche deposition depth patterns across Alaska transportation corridors. Left panel: Mean maximum deposi-tion depth in meters compared between Southcentral (SC) and Southeast (SE) Alaska under 30-year (light blue) and 300-year (dark blue) return periods. Right panel: Mean maxi-mum deposition depth in meters categorized by DOT road functional classification, high-light-ing severe debris accumulation on Arterial corridors exceeding 2.28" m" under 300-year events.

m during 30-year events and 2.28 m during 300-year events (Figure 5).

The Haines Highway represents the largest linear avalanche footprint in Alaska (97.3 km total affected length; 42.5 km at 30-yr and 54.8 km at 300-yr; Figure 6). The Eagle River network accounts for the highest path density (n=1,473), expanding its hazard footprint by 329% under 300-year events.

The Skagway corridor (Klondike Highway) and Seward Highway represent extreme dynamic hazard zones, with maximum impact pressures of 702.1 kPa and 625.7 kPa, respectively (Figure 6).

The quantitative results of this study can form the foundational backbone for a modern, digital Alaska Avalanche Atlas. As experienced maintenance personnel and patrollers retire, unwritten local observations are lost. Automated physics-based avalanche modeling augments observations and establishes a permanent, institutional digital baseline that standardizes hazard data across unmonitored rural corridors, industrial haul routes, remote airstrips, utilities, and planned development where active field patrolling is absent.

During unexpected storm cycles or Search and Rescue (SAR) operations, objective large-scale hazard indication maps provide emergency managers with instant hazard footprints to evaluate secondary avalanche risks to rescue teams.

Furthermore, an objective physics-based hazard indication map provides a reference point for climate change adaptation. Relying on historical observations from previous decades is increasingly unsafe as Alaska's climate is warming rapidly. Shifting precipitation regimes, such as transitions from high-elevation dry-snow avalanches to low-elevation wet-snow or slush-flow hazards, can be dynamically modeled as snowpack temperatures elevate.

Ultimately, the metrics and spatial data produced in this study enable avalanche risk management to transition from reactive operational responses to data-driven capital allocation and proactive infrastructure planning. By leveraging these hazard indication maps, state planners can now systematically evaluate physical risks across major Alaska corridors, empowering them to direct capital to maximize corridor safety and long-term resilience.

4. CONCLUSION

This study delivers the first standardized, statewide, physics-based indication of snow avalanche hazard along Alaska road corridors. By coupling automated release-area delineation and RAMMS::LSHIM simulations with downscaled climate-derived snow inputs, the framework resolves not only potential runout extent but also velocity, flow height, deposition depth, and impact pressure for approximately 30- and 300-year loading scenarios. Across 2,086 road-interaction segments, modeled exposure increases from 317.5 km at the 30-year return period to 625.9 km at the 300-year return period, demonstrating that rare storm conditions substantially expand both the extent and intensity of corridor exposure.

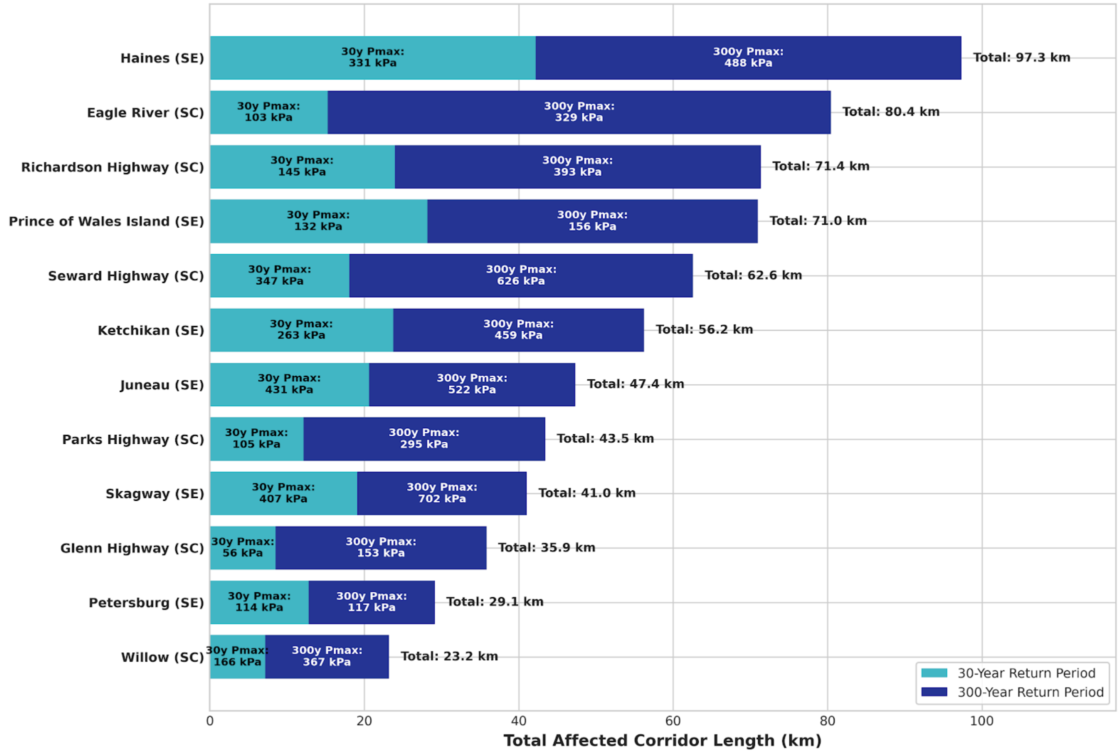

Figure 6: Total affected corridor length in kilometers and segment-specific peak impact pressures for the 12 most avalanche-exposed transportation corridors in Alaska. Bars are broken down into 30-year (teal) and 300-year (dark blue) return period contributions. Individual bar segments record peak impact pressure (P_"max") for both the 30-year and 300-year return periods, while right-side text summarizes total affected corridor length and overall maximum recorded pressure.

The results reveal strong regional and roadway-specific contrasts: Southeast Alaska is characterized by higher-intensity frequent-event impacts, whereas Southcentral Alaska shows the greatest expansion in affected roadway under rare events. Arterial corridors experience the highest modeled pressures and debris depths, while several key routes, including the Haines, Klondike, and Seward highways, emerge as priority hazard corridors. These outputs provide a consistent baseline for identifying locations where more detailed site-specific assessment, monitoring, mitigation, or operational planning is warranted.

Although the maps are not substitutes for local avalanche forecasting or engineering design studies, they address a critical information gap in Alaska's data-sparse mountain terrain. Their principal value is as a regional screening and prioritization tool: a durable digital inventory that can support transportation planning, emergency response, capital investment, and preservation of institutional hazard knowledge. Future work will focus on validation against new avalanche observations, improved forest and land-cover characterization, representation of entrainment and wet-snow or powder-snow processes, and probabilistic treatment of meteorological and model uncertainty. Together, these advances can help move avalanche-risk management in Alaska from predominantly reactive, observation-dependent practice toward proactive, spatially consistent infrastructure resilience planning.

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