

Author response to the referee comments

egusphere-2026-3951. *How exposed is a mountain road to snow avalanches? A corridor-scale assessment in the southern Andes.* Iván Latorre, Marius Schaefer and Felix Oesterle.

We appreciate the careful reviews by Dieter Issler (RC1) and the anonymous Referee 2 (RC2). Following the Overview, Part 1 addresses RC1 and Part 2 addresses RC2; a summary of planned manuscript revisions closes the document. Referee comments appear in italics, followed by our responses and a *Change:* statement identifying the planned revisions. Page and line references identify locations in the discussion paper. We performed additional simulations to quantify the effects of the requested modifications. When preparing the revised manuscript, we will regenerate these numerical results and may refine them.

Overview

We accept the central concerns in both reports. Following the second option offered by RC2, we will explicitly describe our approach as a deterministic corridor-scale exposure assessment grounded in prescribed scenarios instead of probability distributions. The contribution lies in covering the region with locally calibrated, reproducible methods rather than in advancing avalanche dynamics. RC1 recognized its "significant practical value" for countries with exposed traffic routes and limited mitigation resources. The principal revisions will be:

1. Friction. In place of the two-class scheme, we will adopt the smooth-law form proposed by RC1, in which effective friction varies continuously with volume. We used our four events to calibrate and check the separate wet and dry lines, using AIMEC to select the 2011 release depth. We will interpret the calibrated friction values as effective parameters specific to each path (R1.2, R2.1 to R2.4).
2. Entrainment. To test the omission of entrainment, we reran the corridor and calibration simulations with a uniform erodible layer. Section 5.3 will discuss the resulting differences (R2.7, R2.8).
3. Risk. We will add a first-order calculation of road users' individual risk, explicitly parameterized by release probability and road closures (R1.1).
4. Limitations. Section 5.3 will additionally examine release geometry, the design convention based on a three-day snow increase, and snow state and flow regime (R2.9 to R2.16).

We repeated the 624 corridor simulations for each calibrated friction line (Fig. R2) and for the entrainment comparison (R2.7). Exposure retained a similar spatial pattern: road-reaching paths, crossing locations and arrival times changed little. Entrainment chiefly altered the deposits and pressures of individual avalanches.

The revised manuscript will correct errors that our reanalysis identified in the discussion paper: how we described the road-reaching criterion (R1.1); the agreement claimed for the 2022 validation event (R1.2, R2.4); the accepted runs and reference-simulation values for Campanario 2011 (#19, #28); the aspect assigned to wind-loaded slopes and the reference snow depths obtained from the earlier engineering study (#7, #10); and the fracture depth for release area A11-1 in the Severe scenario, entered as 0.09 m rather than 0.90 m. Correcting the depth increased the number of road-reaching simulations by one (528 instead of 527; 177 instead of 176 in the Severe scenario) and left all conclusions unchanged. We will publish the corrected data set through an update to the Zenodo record.

Part 1. Reply to Referee 1 (Dieter Issler)

We are grateful for Dieter Issler's precise and constructive comments, especially the suggested friction interpolation, which we tested throughout the corridor. We accept both major concerns and share his view of the work's novelty.

R1.1 Hazard versus risk

The three assumptions. *"First, they effectively assume that a snowfall with a given return period (10, 30, 100 years) will cause an avalanche in each path along the road with a probability of 100% [...]. Second, the authors also follow the Swiss guidelines by assuming that the release height of the avalanches corresponds to the new-snow height. Third, the authors neglect wind loading or depletion."*

We will make these first two assumptions explicit. Assigning a release probability of one can overestimate the actual value by up to an order of magnitude. Persistent weak layers may yield fracture depths exceeding new-snow depth: on the day of the 2022 event, for example, a snow pit at La Biblioteca showed failure on buried surface hoar at 78 cm. With the smooth law (R1.2), friction decreases continuously as fracture depth increases, eliminating the jump at 10 000 m³. We obtained release depths from the earlier engineering study (Dirección de Vialidad, 2021), which had already adjusted them for wind loading and depletion. The discussion paper described that treatment incorrectly. In that study, the exposure of individual release areas to snow-transporting winds determined the wind factors: positive on loaded lee slopes, negative on windward slopes. This adjustment by release area closely resembled the referee's proposal (#7, #9). *Change:* Sects. 3.1, 3.2 and 5.3.

Individual risk. *"It is, however, desirable, that the analysis be made ready for use in a risk analysis or, even better, include an estimate of individual risk for a car or bus passenger passing this road in winter."*

For a car occupant, we will add a first-order estimate of individual risk of death, following Wilhelm (1998), Zischg et al. (2005) and Hendrikx and Owens (2008). Each road-reaching simulation contributed a product of four factors: the annual probability of its scenario's storm class (1/10 – 1/30, 1/30 – 1/100 and 1/100), release probability, the chance that a car occupied the exposed road segment at avalanche arrival, and lethality increasing with peak pressure at the road. Occupancy probability was the exposed section's driving time divided by the winter season's duration. Summing these products over all simulations yielded a per-trip probability of death; multiplying by the trip count and the fraction of avalanches occurring with the road open gave annual risk. For a road user driving twice daily, the estimated annual risk was on the order of 10⁻³ if every path released during each scenario storm, with no road closures. Release probabilities from 0.1 to 0.3, together with the historical effectiveness of closures documented by Rheinberger et al. (2009), gave annual risks on the order of 10⁻⁵ to 10⁻⁴. For context, the Swiss target is 2×10^{-4} for activities with limited self-determination (Rheinberger et al., 2009), and the upper bound of acceptable risk for road users quoted by Zischg et al. (2005) is 10⁻⁶ to 10⁻⁵. Flow simulations influenced the estimate less than release probability or road management; risk concentrated in a few kilometers, led by the hot spots at km 155, 125 and 127. *Change:* method description in Sect. 3 and a short closing subsection in Sect. 4, with the estimate's limitations (release probability not calibrated, lethality adopted from Alpine and Canadian roads, approximate traffic data, no documented effectiveness for existing closures, summation over sub-paths that may be alternative branches of one release (R2.11), and coverage confined to moving traffic although vehicles waiting at closure points may also be exposed); revision of the abstract and Sects. 5.2.3, 5.3 and 6.

The road-reaching criterion. *"A buffer width of 50 m from the road centerline combined with a peak-pressure threshold of 10 Pa may mean that especially small avalanches releasing close to the road but with short run-out will count as hits even though they never would be able to reach the road in reality. [...]"*

The concern was justified. A check of the implementation exposed a mismatch with Sect. 3.7 (p. 10, ll. 242 to 247). To obtain the published counts, we sampled points along the road centerline in the peak-pressure raster, without a buffer. We classified runs as road-reaching if any sampled point returned pressure above zero. This implementation imposed a stricter test than we had described: sampling followed the centerline rather than a 50 m buffer, and all simulations counted as road-reaching also exceeded the stated 10 Pa threshold. Counts changed little with the pressure threshold. Among the 624 simulations, thresholds of 0, 3 and 10 kPa gave 528, 524 and 490 crossings, respectively, including the A11-1 correction (Overview); imposing a flow-thickness minimum of 0.1 m gave 526. Applying a 50 m buffer raised the total by about 6 %. In AvaFrame's com1DFA dense-flow module, simulations ended according to the kinetic-energy criterion (1 % of peak kinetic energy), which stopped thin or creeping fronts from advancing indefinitely. *Change:* Sect. 3.7 will document the implemented criterion and the sensitivity of counts to buffer width and pressure threshold.

R1.2 Calibration of the friction coefficient

"First, the second Campanario avalanche with a volume of 9,100 m³ [...] falls below the proposed threshold of 10,000 m³, so it should be simulated with $\mu = 0.31$ according to the authors' recipe. Second, it is well known that dry-snow avalanches can have significantly lower friction than wet-snow ones of comparable volume. Third, an abrupt increase of μ by 0.11 at the transition from 'large' to 'small' avalanches is not physically plausible [...]"

These three objections are valid. We will use the referee's proposed form, $\mu = a - d \log_{10} V$, for a smooth law with separate wet and dry lines, replacing the two-class scheme; V is release volume (m³) on the model terrain. As the referee envisaged, we calibrated the constants from our events instead of using his tentative values. We used documented fracture depths except for Campanario 2011, where no observation was available. Among runs meeting the criteria in #19, AIMEC selected 0.60 m as the best match to the mapped deposit. Denser sweeps (μ increments of 0.005) identified friction compatible with observations at these depths. We passed the wet line through the best-constrained calibration on each path: La Biblioteca, 15 October 2018 ($\mu = 0.31$; 3 430 m³; accepted range 0.295 to 0.33), and Campanario 2011 ($\mu = 0.20$; 78 400 m³; 0.195 to 0.205). These were the discussion paper's two calibrated values and gave $\mu_{\text{wet}} = 0.60 - 0.081 \log_{10} V$. Agreement with the 7 October 2018 event (0.31; accepted range 0.275 to 0.41) provided a further check: the event crossed the road, but its runout beyond the crossing was unobserved. One dry event could determine only the dry line's level. We retained the wet line's slope and passed the dry line through Campanario 2022 (0.17 at the 0.78 m fracture depth from the snow pit; accepted range 0.155 to 0.19): $\mu_{\text{dry}} = 0.50 - 0.081 \log_{10} V$. Both lines were truncated at the lower bound $\mu = 0.155$, the standard value for extreme dry avalanches above about 1 300 m (Buser and Frutiger, 1980; Salm et al., 1990). This bound was reached at about 18 000 m³ on the dry line and 310 000 m³ on the wet line (Fig. R1). The slope was consistent with Swiss practice: the dry-snow volume classes of Gruber and Bartelt (2007) imply about 0.05 to 0.09 per tenfold increase in volume. The unobserved 2011 release volume nevertheless left it poorly constrained: the depths that AIMEC matched to the mapped deposit (0.50 to 0.90 m) yielded slopes from 0.055 to 0.10. For comparison, the constants tentatively suggested by the referee (0.50, 0.44 and 0.06) gave similar friction over 3 000 to 80 000 m³ and nearly identical corridor results (510 versus 507 road-reaching simulations with the wet line). We then simulated the 208 release areas under all three scenarios with each calibrated line (Fig. R2):

- among the 624 simulations, the two-class scheme produced 528 crossings, the wet line 507 and the dry line 586; varying the 2011 release depth over the depths matched by AIMEC (0.50 to 0.90 m) yielded about 470 to 535 crossings for the wet line;
- the wet line preserved the order of the three principal hot spots, counted over the three scenarios as in Fig. 5b (km 155, 110 and 127); under the dry line, km 128 ranked above km 127; road-arrival times barely changed;
- peak pressure at crossings shared by the two-class run and the run for each friction line was slightly lower under the wet line (median -6%) and higher under the dry line (median $+34\%$); the dry line applied its lower bound on μ in 439 of the 624 simulations.

The wet and dry lines bracketed the corridor totals of the two-class scheme, which lay nearer the wet-line values. For the base case, we propose the wet line, while reporting a band for each kilometer and the dry-line results as an upper envelope. Three of the four calibration events favored this choice: both La Biblioteca avalanches followed pronounced warming, with a daily maximum of $14\text{ }^{\circ}\text{C}$ before 7 October and maxima up to $18\text{ }^{\circ}\text{C}$ in the days preceding 15 October 2018, recorded about 200 m above the path. The 2011 avalanche at Campanario was a wet-snow event. Dry storm-snow avalanches also occur along the corridor: on 2 July 2022, Campanario experienced a slab and powder-cloud event. Warm storms, rain on snow and the spring thaw trigger wet or melt avalanches, with examples from Campanario in October 2011 and July 2020. The central Andes face a recognized wet-snow avalanche hazard (Vera Valero et al., 2015, 2016). Without a systematic corridor register that distinguishes snow-moisture classes, the frequency of wet avalanches relative to dry ones remains unknown; the dry line is therefore still needed to define the upper envelope. *Change:* Sects. 2 and 3.6, results in Sect. 4 (Table 3, Figs. 4 and 5), abstract and conclusions.

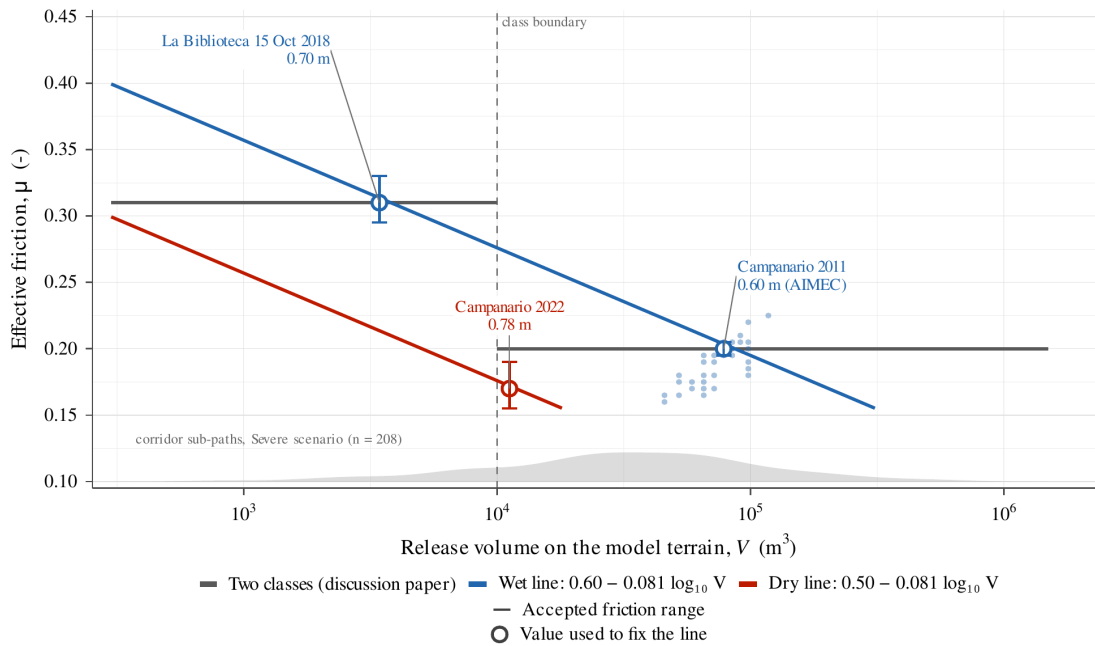


Figure R1. Effective friction as a function of release volume, comparing the discussion paper's two-class scheme with our calibrated wet and dry lines. Both lines extend down to the lower bound $\mu = 0.155$, which applies above roughly $18\,000\text{ m}^3$ on the dry line and $310\,000\text{ m}^3$ on the wet line. Vertical bars mark the friction ranges reproducing observations in the denser sweeps at documented release depths or, for Campanario 2011, at the 0.60 m depth chosen with AIMEC. Circles identify the values anchoring the lines; small dots identify the 32 Campanario 2011 runs meeting the criteria in #19 across the tested release depths (R2.2). Grey shading shows the distribution of Severe-scenario release volumes for the 208 sub-paths. Volume was calculated on the model terrain; using the planimetric convention of the discussion paper instead places the 2022 event (about $9\,100\text{ m}^3$) below the $10\,000\text{ m}^3$ boundary.

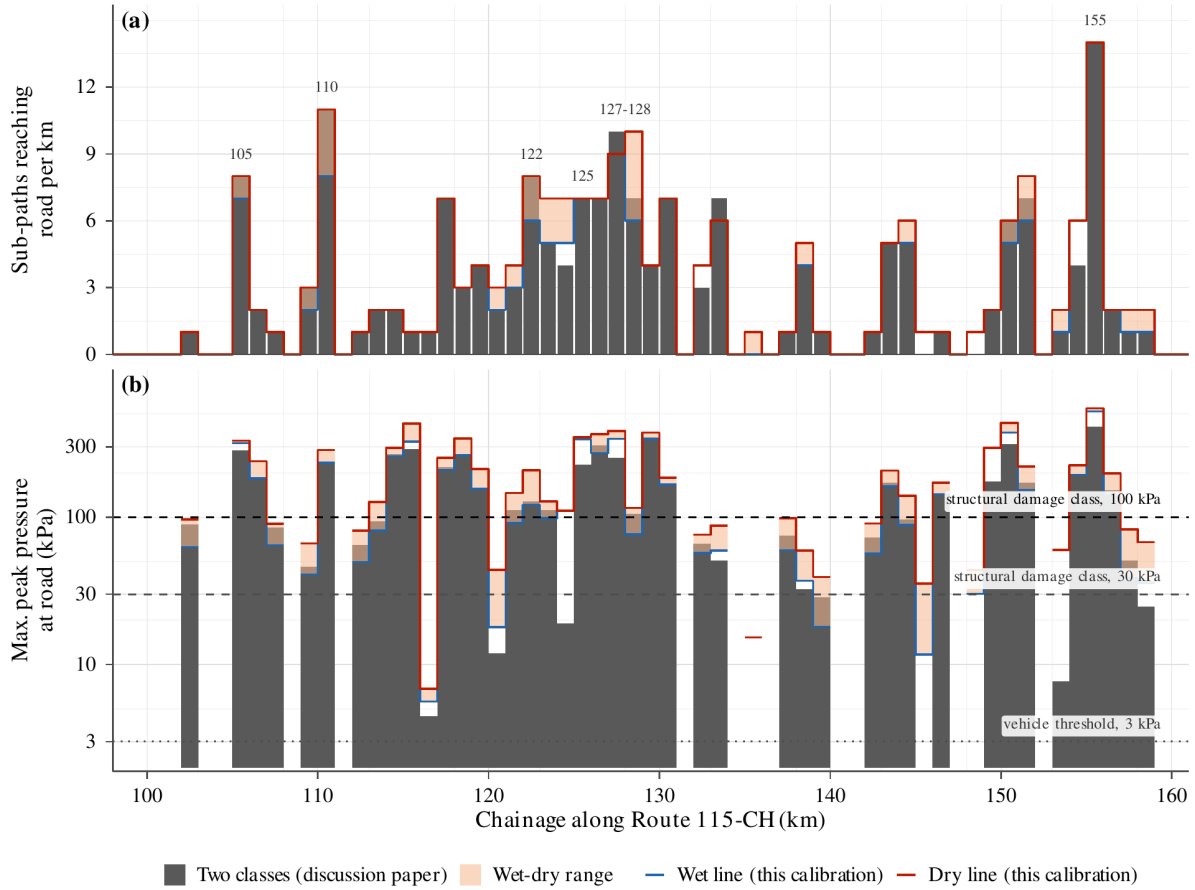


Figure R2. Corridor results after rerunning the simulations with the calibrated smooth law. For the Severe scenario, the panels show how the wet and dry lines compare with the two-class scheme: (a) road-reaching sub-path counts by kilometer and (b) maximum peak pressure at the road. In panel (b), horizontal lines indicate the vehicle threshold of 3 kPa and structural damage classes of 30 and 100 kPa. Labels in (a) mark the hot spots identified in the discussion paper.

Wet versus dry, and the validation event. *"The authors' approach is, however, problematic for the Campanario avalanche because one event is a large wet-snow avalanche and the other a small dry mixed-snow event. It is therefore not too surprising that $\mu = 0.20$ fitted both events."*

We agree: the distinction is valid, and the agreement claimed in the discussion paper for 2022 at $\mu = 0.20$ was overstated. Applying the corridor procedure at the road centerline, we reassessed all 16 validation runs. Without entrainment, only $\mu \leq 0.19$ produced road-reaching flow. The reported deposit was about 1.8 m thick, which no tested friction reproduced; at $\mu = 0.20$, the run shown in Fig. 3c ended about 70 m upslope of the road. At the 0.78 m release depth, runout thus limited compatible friction to 0.155 to 0.19; our calibrated dry line used 0.17 within that interval. Adding the erodible layer from R2.7 produced road-reaching flow with deposit thicknesses of 1.2 to 1.8 m for $\mu = 0.15$ to 0.20, closest to the reported value at 0.19; agreement with reported runout required $\mu = 0.22$ to 0.23 (Fig. R3). For dry avalanches on this path above about 18 000 m³, the dry line uses the lower bound $\mu = 0.155$ (#21). *Change:* Sects. 4.1, 5.1 and 5.3, Table 2 and Fig. 3c; use of the 2022 event to anchor the dry line, replacing its role as validation for $\mu = 0.20$.

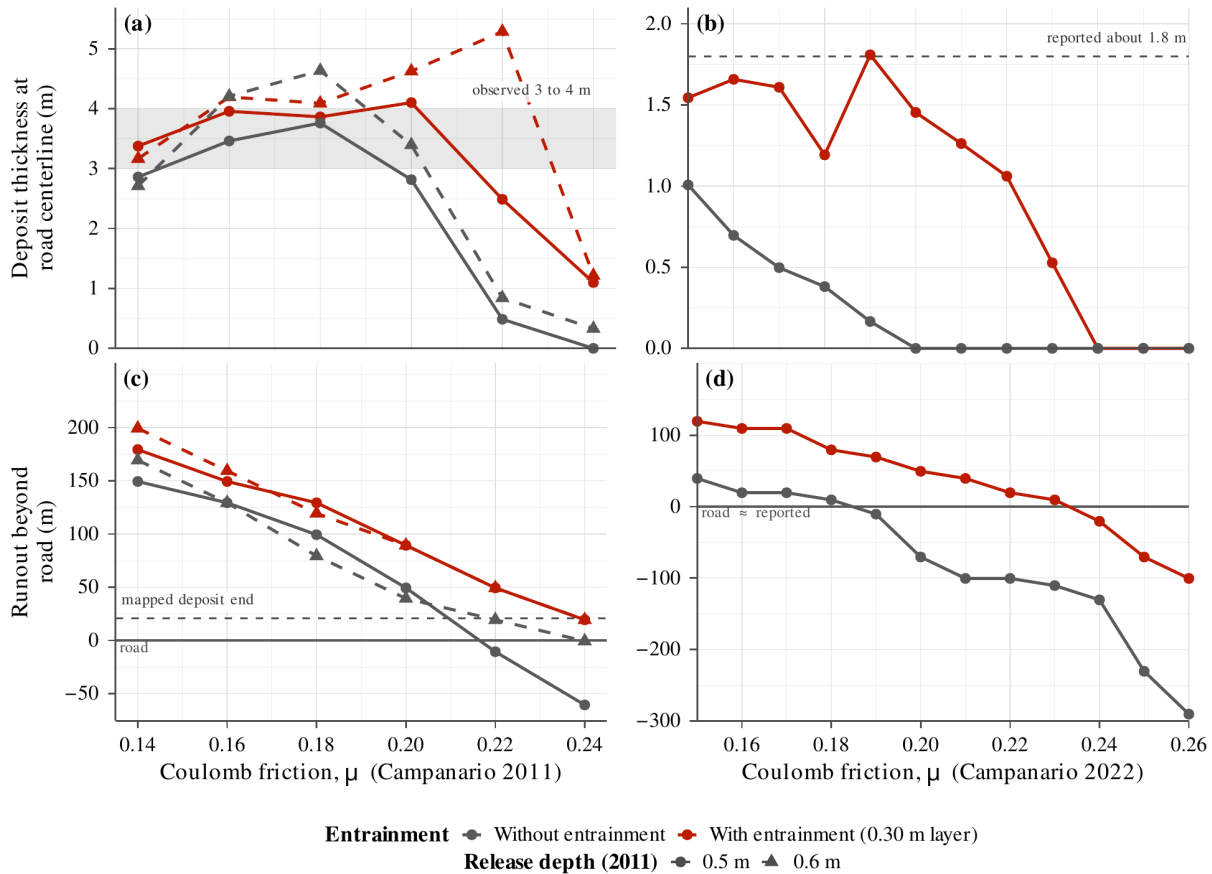


Figure R3. Back-analyses for Campanario 2011 and 2022 using either no entrainment or a uniform erodible layer of 0.30 m. The plots show how road-centerline deposit thickness (top) and thalweg runout beyond the road (bottom) varied with friction. Event records provide the comparison: observed deposit thickness (a, b); the lower end of the 2011 deposit delineated in Landsat imagery, 21 m past the road (c); and the 2022 runout ending a few meters past the road barriers (d). For 2011, lines show release depths of 0.50 m (the discussion paper's reference run) and 0.60 m (selected with AIMEC). Road reach was judged on the road centerline and runout along the thalweg, so flow can reach the centerline while thalweg runout ends short of the road (2022, $\mu = 0.19$, without entrainment).

Minor issues: the 37 annotations

#1 (p. 1) "This pressure threshold looks awfully high to me. [...] the vehicle-destruction threshold of 100 kPa might be appropriate for a tank but not for a passenger car or normal truck."

The referee is right: our discussion paper applied 30 and 100 kPa, taken from structural damage thresholds (#13), to vehicles by analogy. We will label these values as structural intensity classes and adopt a vehicle threshold of 3 kPa. For a car presenting a side area of 6 m², that pressure exerts a force comparable in magnitude to the car's weight. Almost every simulated crossing exceeded that value (524 of 528). *Change:* abstract, Sects. 3.1, 3.7, 4.4.1, 4.6, 5.2.3, 5.3 and 6, Table 3.

#2 (p. 1) The abstract will use "would reduce collective risk most". *Change:* abstract.

#3 (p. 2) Our amended description will explain that NAKSIN also calculates runout using a thickness-averaged Voellmy-type model for release areas with release probability above a threshold. *Change:* Sect. 1.

#4 (p. 3) The revised wording will be "allowed reopening the road". *Change:* Sect. 2.

#5 (p. 4) We will expand the main map of Fig. 1 to occupy two columns. *Change:* Fig. 1.

#6 (p. 5) *"The reason for doing so and the exact way it was done need to be explained."* (slope factor)

We used the factor provided by the earlier engineering study (Dirección de Vialidad, 2021, p. 26). It reduced new-snow depth according to each release area's mean slope to account for less snow remaining on steeper terrain before failure. The tabulated values were within 0.006 of $0.8 \times 0.291/(\sin \psi - 0.202 \cos \psi)$; the function of slope angle ψ specified by the Swiss guidelines (Salm et al., 1990), multiplied by 0.8. That study did not identify the multiplier's origin. *Change:* Sect. 3.2.

#7 (p. 5) *"Is there a good reason to assume that only south-easterly winds will produce wind-loading in this complex terrain?"*

No: the discussion paper misstated the aspect of the wind-loaded slopes. The earlier engineering study found that snow-transporting winds originated almost entirely between west-northwest and north-northwest. They deposited snow on lee slopes facing southeast, rather than on northwest-facing slopes. The study's wind factors depended on how each release area was exposed, with no single aspect prescribed (R1.1). *Change:* correction of Sect. 3.2.

#8 (p. 5) We agree that a car may also be displaced downslope (#1). We will describe two mechanisms in Sect. 3.1: structural damage and displacement of a vehicle off the road. Lethality values incorporated displacement in our risk calculation. *Change:* Sects. 3.1 and 5.2.3.

#9 (p. 5) *"Is this the dominant wind direction under snowfall in the study area? Perhaps give a little more information on the criteria used for delineation of PRAs."*

Snow-transporting winds originated between west-northwest and north-northwest (#7). To delineate release areas, experts in the earlier engineering study considered slope (excluding release below 26° or above 60°, with the most critical slopes between 30° and 50°), the absence of any convex break in the direction of flow, exposure to wind from these directions, and field observations and testimony gathered during three winters (Dirección de Vialidad, 2021, pp. 9, 12 and 13). *Change:* Sect. 3.2 will set out these documented delineation criteria; the study gives no description of the satellite-image analysis cited by the discussion paper.

#10 (p. 5) *"Since the extreme scenario with a return period of 100 y is beyond the period for which there are recorded observations, you should explain in more detail how you arrived at these values."*

The earlier engineering study estimated new-snow depths at 2 000 m using the regional frequency analysis by the Chilean water directorate (DGA) for maximum one- to three-day precipitation. With an assumed density of 200 kg m^{-3} , the calculation converted precipitation to snow for storms lasting 2, 2.5 and 3 days ($T = 10, 30$ and 100 years; Dirección de Vialidad, 2021, pp. 18 to 25). Regional statistical extrapolation thus provided the 100-year value. The correct reference depths were 110, 152 and 218 cm; our discussion paper mistakenly reported 110, 122 and 140 cm, which corresponded to the 10-year values for those durations. Every simulation used the correct set. *Change:* correction and completion of Sect. 3.2.

#11 (p. 5) *"What kind of model is it, and what does 'site-specific' mean here?"*

We introduced this misleading expression, which called a three-step calculation a model. The earlier engineering study combined new snow for the design storm, wind deposition and a slope factor, together with the elevation corrections detailed in #12. *Change:* Sect. 3.2 will replace the expression with this description.

#12 (p. 5) *"Are you assuming that the snowfall height is an exponential function of altitude? If so, what is the basis for this assumption?"*

Elevation entered through a linear correction: each 100 m of elevation gain above 2 000 m added 6 % of the reference depth at 2 000 m. Its basis was the 12 % difference in mean snow depth between Lo Aguirre (2 000 m)

and Laguna del Maule (2 200 m). Below 1 600 m, depths were reduced (Dirección de Vialidad, 2021, pp. 23 and 26). *Change:* Sect. 3.2.

#13 (p. 5) The source of the 30 and 100 kPa thresholds was McClung and Schaerer (1993, *The Avalanche Handbook*); our discussion paper credited Keylock and Barbolini (2001), who reproduced them. *Change:* Sects. 3.1 and 5.2.3.

#14 (p. 5) We will change "undefended structures" to "non-reinforced concrete structures". *Change:* Sect. 3.1.

#15 (p. 6) *"Specify whether this [value] is measured vertically or normal to the slope."* (78 cm)

The snow-pit report of 2 July 2022 (Viento Puelche, 2022b) left the measurement direction unspecified. We took 78 cm from that report for the discussion paper: it was the depth beneath the snow surface where 13 taps in a compression test caused failure on buried surface hoar. The pit was dug and the test performed on the 2022 event date at La Biblioteca: it was 1.52 m deep, on a 40° slope, about 5 km from Campanario's release area. For com1DFA, a vertical reading would correspond to 0.60 m measured normal to the slope. Rerunning the 2022 back-analysis with 0.60 m lowered the compatible friction by roughly 0.01 and left our conclusions unchanged. *Change:* Sect. 3.3 and Table 1 will explain the measurement and associated uncertainty and cite the snow-pit report; "CT12" will be replaced by the reported 13 taps.

#16 (p. 8) Because R is dimensional, we will give its value as $R = 0.05$ m. *Change:* Sect. 3.4.

#17 (p. 8) *"The deposit density differs often considerably from the flow density [...]. The way this was done needs to be fully explained."*

We will explain the basis of the comparison. Density stayed fixed in com1DFA (i.e., compaction was not modeled). We compared the simulated flow thickness at the end of the simulation, when the flow had come to rest (not the peak flow thickness named on p. 8, ll. 191 to 192), with the reported deposit thicknesses. This was a meaningful comparison for the 2011 wet event (470 kg m^{-3}) against its observed 3 to 4 m range. For the 2022 dry event (200 kg m^{-3}), that comparison was only indicative; the revised manuscript will therefore rely on this event chiefly to constrain runout (R1.2). *Change:* Sects. 3.4, 3.5 and 4.1.

#18 (p. 8) *"What does this mean for the value of τ_0 ?"*

The value of τ_0 is unaffected: all available parameter sets for com1DFA's samosATAuto option specify $\tau_0 = 0$, with μ alone distinguishing volume classes. *Change:* a clarifying sentence after Eq. (1).

#19 (p. 8) *"It remains unclear to me how you quantified the quality of each simulation."*

Our discussion paper did not describe the evaluation adequately. We reevaluated the 130 Campanario 2011 simulations against three criteria: road deposit thickness within 3 to 4 m; a simulated deposit centroid inside the outline mapped from a Landsat 5 image with the normalized difference snow index; and runout reaching that outline's lower end, with overshoot limited to 100 m. This allowance reflected the 30 m pixel size and uncertainty in locating the mapped toe. All three criteria were satisfied by five runs, with $\mu = 0.18$ to 0.21 (the discussion paper reported 12 runs with $\mu = 0.18$ to 0.22; p. 11, ll. 264 to 265). For this response, a denser sweep of 228 simulations (μ increments of 0.005; release depths from 0.35 to 0.90 m) yielded 32 accepted runs with $\mu = 0.16$ to 0.225 and release volumes spanning a factor of 2.6. Removing the overshoot cap of 100 m raised the accepted total to 57, with friction down to the sweep's minimum (0.15); reaching the mapped toe remained a requirement (R2.2). Section 4.1 will report the accepted set and friction interval defined by these criteria. For La Biblioteca, evaluation relied on the deposit at road level and on observed runout. *Change:* Sects. 3.5 and 4.1.

#20 (p. 9) We will use smooth interpolation for $\mu(V)$ (R1.2). *Change:* Sects. 3.6 and 4.

#21 (p. 9) *"What would one expect to happen if a dry-snow avalanche of more than 60,000 m³ was released?"*

At that release volume, the dry line assigns $\mu = 0.155$, its lower bound and the standard friction for extreme dry avalanches (Buser and Frutiger, 1980; Salm et al., 1990). The event in 2022 anchored the calibration of this line (R1.2). A wet avalanche of the same volume would receive $\mu \approx 0.21$, so the dry avalanche would run farther. *Change:* Table 2, Sects. 4.1 and 5.1.

#22 (p. 10) *"It is not obvious to me (and probably to other readers) why the thalwegs would be needed in the calibration process, so please explain briefly."*

We sampled com1DFA rasters along the road to calculate road-reaching counts and pressures, exposed lengths and arrival times, without using thalwegs. Thalwegs served only to construct AIMEC calibration profiles and calculate the runout-length statistics in Figs. 5c and 6. We measured calibration runout to the last point on the thalweg with deposit thickness above 0.05 m. This was similar to the lowest-pixel criterion suggested in the comment. *Change:* Sect. 3.6 and the captions of Figs. 5 and 6, with the uncertainty of the runout-length statistics stated explicitly.

#23 (p. 10) *"This condition looks unrealistic because real snow avalanches stop way before they thin out to 1 cm."*

The 0.01 m value set a mask for identifying the flow front when extracting thalwegs. It governed neither termination nor road-reaching classification. Simulations ended according to com1DFA's kinetic-energy criterion (R1.1). *Change:* Sects. 3.4 and 3.6.

#24 (p. 10) Crossing counts were based on the road centerline, with no buffer (R1.1). *Change:* Sect. 3.7.

#25 (p. 10) The 10 Pa threshold refers to no measuring instrument, so the parenthetical "(~ instrument noise level)" will be removed. *Change:* Sect. 3.7.

#26 (p. 10) *"Flow depths below 0.1–0.2 m are hardly ever observed in Nature, and they might at most affect a bicycle, but not a car."*

Such thin flows cannot be interpreted as physical deposits. Requiring centerline flow thickness of at least 0.1 m, the lower end of the referee's range, lowered the total only from 528 to 526 simulations; thin margins therefore did not inflate the count. We will report intensities at crossings relative to thresholds of 3, 30 and 100 kPa (#1). *Change:* Sect. 3.7.

#27 (p. 11) With its reported volume of 9 100 m³, the 2022 event would have received $\mu = 0.31$ under the discussion paper's two-class scheme because of its 10 000 m³ threshold, exposing the rule's inconsistency (R1.2). We will remove "confirming $\mu \approx 0.20$ as representative for large avalanches" (p. 11, l. 280) and "independently confirms $\mu \approx 0.20$ " (p. 20, ll. 459 to 460). *Change:* Sects. 4.1, 5.1 and 5.3; Fig. 3c.

#28 (p. 11) *"[...] It is debatable whether this counts as robustness."*

Road-level peak pressure ranged from 26 to 54 kPa among the five simulations accepted under #19. That variation did not support the description "robust". We will correct the reference-simulation values reported in our discussion paper (p. 11, ll. 266 to 267): the run (released at 0.50 m, which Table 1 lists as 60 cm) produced a 2.8 m deposit at road level, just below the 3 to 4 m range we claimed to match, and a peak pressure of 23 kPa rather than approximately 40 kPa. *Change:* Sect. 4.1 and Table 1.

#29 (p. 12) We will provide matching plots for the other three events. *Change:* Fig. 3.

#30 (p. 16) The problems with Figs. 5c to 5e are real: the symbols are indistinguishable, and the Moderate scenario has a different point count from panel (b). We will give panels (c) to (e) the color scheme used in panel

(b). The revised caption will explain the counting: panel (b) represents a sub-path only once, for its lowest road-reaching scenario, whereas panel (c) plotted all three scenarios of the 189 road-reaching sub-paths, including 27 Moderate runs that stopped short of the road; the revised panels (c) to (e) will show only road-reaching simulations. *Change:* Fig. 5.

#31 (p. 17) The citation will change from Martini et al. (2023) to Wirbel et al. (2026, EGU sphere preprint egusphere-2025-6053). *Change:* Sect. 5.1.

#32 (p. 21) We will add Bühler et al. (2011), whose similar findings preceded those of Miller et al. (2022). *Change:* Sect. 5.3.

#33 (p. 21) *"The results of Bühler et al. (2011) suggest that the original resolution of the DEM should be sufficient except perhaps for the smallest avalanches and that the quality of the DEM is more important."* Our revised discussion will draw on Bühler et al. (2011), who found a resolution of about 25 m sufficient for large avalanches, considered DEM quality and resolution even more critical for the medium and small avalanches that threaten roads, and recommended checking DEMs for artifacts. Resampling at 5 m served to define a convenient computational mesh and supplied no additional information. *Change:* Sect. 5.3 and abstract.

#34 (p. 22) Figure 6 needs larger text; we will increase its font size. *Change:* Fig. 6.

#35 (p. 24) We will recommend event documentation and cameras in place of an instrumented test site. *Change:* Sect. 6.

#36 (p. 28) Title capitalization will be removed from the Rheinberger et al. (2009) reference. *Change:* reference list.

#37 (p. 30) The Wilhelm (1998) entry will be completed with details of the volume (*25 Years of Snow Avalanche Research*, Voss, 1998, edited by E. Hestnes, NGI Publication 203). The BibTeX record supplied in the annotations describes another contribution to that volume, authored by Harbitz et al. We will retain Wilhelm's authorship and leave the contribution title and pagination unchanged. *Change:* reference list.

Part 2. Reply to Referee 2 (anonymous)

We are grateful for this careful, rigorous review and share its central assessment. We used a depth-averaged dense-flow model to assess corridor exposure deterministically, with release polygons defined in advance and fracture depths linked to return periods. Storm history, snow state, entrainment and changes in flow regime were not represented in these calculations. We chose the second option proposed at the report's close and will frame the revised manuscript on that basis (Overview). We will recast wording that implies a wider scope: "physically calibrated simulations" (p. 3, l. 68), the introduction's final sentences (p. 3, ll. 71 to 75), "the friction scaling derived here" (p. 22, l. 521) and the first conclusion (p. 23, ll. 536 to 538).

General comments

R2.1 *"If the model cannot represent the changing flow state caused by snow properties and entrainment, then the calibrated friction coefficient inevitably becomes an effective parameter absorbing processes that are missing from the model. A fitted value such as $\mu = 0.20$ therefore cannot straightforwardly be interpreted as an intrinsic friction coefficient characteristic of 'large avalanches'."*

The fitted μ described effective friction specific to each path, absorbing effects of entrainment, the snow state and the flow regime. Section 3.4 will state this interpretation and specify that we deliberately omitted entrainment in the corridor simulations. A smooth law will interpolate between these effective calibrations as a function of release volume, using RC1's proposed form, with constants we calibrated against our events (R1.2). This treatment will follow the Swiss guidelines (Salm et al., 1990) and com1DFA's samosATAuto option; we will assign no physical interpretation to the law. *Change:* Sects. 3.4 and 3.6.

1. Calibration and the interpretation of Section 5.1

R2.2 *"For the Campanario 2011 event, neither the release depth nor the release volume is independently constrained. [...] Release volume and friction are fitted simultaneously and may compensate for one another. This is a classical equifinality problem."*

The 2011 calibration was subject to equifinality: we jointly fitted release depth and friction, with no measurement of release volume. We reevaluated all 130 runs using the three criteria described earlier (#19 in Part 1). Deposit thickness alone could not resolve the ambiguity: runs with a road deposit 3 to 4 m thick had friction from 0.14 to 0.21 among these runs and from 0.15 to 0.225 in the denser sweep (#19), where accounting for the deposit's mapped extent narrowed the interval only slightly. That sweep yielded 32 runs satisfying all three criteria, with friction of 0.16 to 0.225 and release volumes spanning a factor of 2.6 across the entire tested depth range. Omitting the overshoot limit of 100 m extended the accepted friction range down to 0.15. Increasing release volume required greater friction within the accepted set. The calibration thus bounded effective friction for the path while leaving release volume undetermined; we used AIMEC to choose among the accepted release depths when calibrating the smooth law (R1.2). Because the 2011 volume that anchors the wet line was itself fitted, the volume dependence it supports remains partly circular; R1.2 reports the consequences (slopes of 0.055 to 0.10 and about 470 to 535 crossings). *Change:* Sects. 3.5 and 4.1 will report the evaluation criteria and results and reconcile "varies only the Coulomb friction μ " (p. 8, l. 198) with the sweep in fracture depth (p. 9, l. 203).

R2.3 *"The available data therefore establish two path-specific effective friction values, but they do not demonstrate that the difference between $\mu \approx 0.20$ and $\mu \approx 0.31$ is caused by avalanche volume." and "Section 5.1 should therefore be reformulated much more cautiously."*

Volume by itself cannot explain why the two path calibrations differed. Measurements from the model terrain put Campanario's length at about 2 km and its elevation loss at roughly 1 000 m; La Biblioteca's paths were shorter than 150 m, with elevation losses under 100 m. Section 5.1 will present the effective calibrations of Campanario and La Biblioteca as the basis for our extrapolation throughout the corridor. The potential for entrainment also varied substantially between these paths (R2.7). The smooth law uses volume alone to index effective friction within each line; Sect. 5.3 will identify this simplification. *Change:* Sects. 5.1 and 5.3 and the first conclusion; bring the path dimensions in Table 1 and Sect. 5.3 into agreement.

R2.4 *"Its release volume is estimated at approximately 9,100 m³, which places it below the manuscript's 10,000 m³ threshold and would therefore assign it to the $\mu = 0.31$ class. [...] This appears to contradict the proposed class boundary rather than validate it."*

We accept the objection to the class boundary and recognize that the discussion paper overstated how well this event was reproduced. Reassessment at the road centerline found road-reaching flow only for $\mu \leq 0.19$ when entrainment was omitted. The $\mu = 0.20$ run shown in Fig. 3c stopped about 70 m upslope of the road; no friction value reproduced the reported deposit of approximately 1.8 m there (R1.2 in Part 1). We therefore found no support for the statement that $\mu = 0.18$ to 0.22 "best reproduced the observed deposit" (p. 11, ll. 276 to 277) or for validating the class boundary. At the 0.78 m release depth, we anchored the dry line at 0.17 (R1.2). The erodible layer in R2.7 enabled road-reaching flow with a deposit thickness near the reported value (Fig. R3). We will adopt the calibrated smooth law in place of the two-class scheme to assign effective friction (R1.2; Figs. R1 and R2). *Change:* Sects. 4.1, 5.1 and 5.3, Table 2 and Fig. 3c.

R2.5 *"At most this provides a qualitative plausibility check."*

Earlier Chilean studies will provide only a qualitative check on plausibility in our discussion (Sect. 5.1, p. 17, ll. 346 to 355). We will cite the model intercomparison by Wirbel et al. (2026) in place of Martini et al. (2023). *Change:* Sect. 5.1.

R2.6 *"It is therefore not possible to attribute a factor-of-several pressure difference to any particular factor or conclude that the previous design basis is systematically biased low. The argument is further weakened by the fact that the manuscript invokes the previous study's use of $\rho = 250 \text{ kg m}^{-3}$ as a possible reason for lower pressures, although its own baseline simulations use the same value."*

Both objections are valid. The revised paragraph will compare how the design bases differed in terrain representation, dynamics formulation, friction law, post-processing and release rule, without declaring either superior. The earlier engineering study assumed partial releases, typically from 25 to 75 % of a polygon's area; we released each polygon completely. The density explanation will be removed, along with "release depths inferred from only three winters", "four compounding factors bias them low" and "systematically below" (p. 17, ll. 363 to 367). We will amend the statement (p. 17, l. 360) that seven of 65 road-reaching release zones had been simulated in the earlier engineering study. That study simulated 29 release areas in seven zones; the count of 65 referred to road-reaching catchments under our Severe scenario. *Change:* Sect. 5.1.

2. Neglect of entrainment

R2.7 *"The neglect of entrainment is, in my view, a major physical limitation rather than a secondary caveat." and "[...] the apparent difference between $\mu \approx 0.20$ and $\mu \approx 0.31$ could be influenced not only by volume and path geometry but also by very different opportunities for mass entrainment."*

We agree that omitting entrainment was a major physical limitation. To assess its influence, we used the entrainment option in com1DFA. We lacked observations to constrain erodible snow on these paths, so we specified an erodible layer of uniform thickness, 0.30 m, excluding release areas, and used an entrained density of 200 kg m^{-3} with default erosion parameters. Over steep rock, this assumption tends to overestimate entrainment. The comparison yielded the following results (Fig. R3):

- For Campanario 2011, simulated entrainment added roughly half as much mass as was released. This likely overestimated the actual contribution because snow may not have covered the entire lower path. Landsat imagery nine days before the October event showed snow cover extending down the path past the road; a week after the event, slopes below about 1 800 m appeared largely bare. To reproduce observed runout, friction had to increase by 0.02 to 0.03; a lower release volume could have yielded the observed deposit. These results illustrated the referee's point about the trade-off among release volume, friction and entrained mass.
- For the small event in 2022, the mass entrained was 1.4 to 1.7 times that released; without entrainment, we could not reproduce the reported deposit (R2.4).
- The short La Biblioteca paths entrained less than 7 % of the released mass, and calibrated friction shifted by under 0.01. Thus, entrainment explained only a minor part of the difference between the two path calibrations.
- Across all 624 corridor simulations, run with the two-class friction, entrainment produced 10 additional crossings and eliminated 3, with little change in which paths reached the road. These removed crossings were marginal, with peak pressure no higher than 3.2 kPa in runs that omitted entrainment. In com1DFA, snow is at rest when entrained, and accelerating it can slow the avalanche. Arrival times and the main hot spots barely changed; scenario medians of peak pressure rose by 10 to 25 %, although the median change at shared crossings was +2 %.

Change: Sect. 3.4 will describe the deliberate choice to omit entrainment in the corridor simulations; Sect. 5.3 will summarize the findings, with an appendix containing the figures.

R2.8 *"[McClung] notes that entrainment can increase total mass very substantially, in extreme cases approaching an order of magnitude beyond the initial slab mass." and "There are in fact at least three different quantities: V_{release} , $V_{\text{flow}}(x, t)$, V_{deposit} . They are not interchangeable."*

Release, flow and deposit volumes cannot be used interchangeably. Section 3.4 will separate these quantities and specify that release volume is the index used for friction. References to McClung (2009) and Sovilla et al. (2006) will support the account of mass gain in large avalanches in Sect. 5.3. In the comparison, the uniform erodible layer raised the small 2022 event's flowing mass to approximately 2.6 times the mass released; for the large 2011 event, entrainment added roughly half the starting mass (R2.7). Effective friction tied to release volume therefore describes mobility along the whole avalanche path and incorporates effects of processes omitted by the model.

Change: Sects. 3.4 and 5.3.

R2.9 *"Perturbing μ and density while keeping release geometry and the no-entrainment assumption fixed quantifies numerical model sensitivity, but it does not explore what may be one of the dominant missing physical processes."*

The sensitivity analysis examined friction and density uncertainty while retaining a fixed model structure. Release geometry, entrainment and snow state were beyond its scope. We will define these limits in Sects. 3.6 and 5.3, report the entrainment comparison as a separate analysis and narrow the fifth conclusion's claim of robustness to this scope. *Change:* Sects. 3.6, 5.3 and 6.

3. Release geometry, probable release areas and the meaning of avalanche volume

R2.10 *"[...] it means the analysis answers the question: What happens if these predefined polygons release with the prescribed depth? It does not answer: What are the possible avalanche releases along this corridor, with what plausible dimensions and probabilities?"*

That distinction is correct; Sects. 3.2 and 5.3 will state it explicitly. On the model terrain, measurements identified the 208 polygons as envelopes of potential release terrain, rather than outlines of individual slabs. Under the Severe scenario, the length-to-depth ratio had a median of approximately 300; McClung (2009) reported approximately 100 for dry slabs. The releases documented in photographs occupied 5 to 44 % of the respective mapped polygons, and the back-analyzed 2011 release 94 %. We will therefore explain that upper-limit volumes resulted from the design convention of releasing each polygon completely. The revised text will also separate the discussion paper's planimetric volumes from those computed on the model terrain for the smooth friction law. The latter averaged 20 % more. Because the smooth law assigns friction from release volume, Sect. 5.3 will also state that these upper-limit volumes lower the assigned friction. *Change:* Sects. 3.2 and 5.3.

R2.11 *"Where many sub-paths are assigned to a single broad catchment, it is not obvious whether these should be interpreted as statistically independent avalanche sources or as alternative branches of a larger possible release."*

The sources cannot be regarded as independent. Each simulation released the polygon for one sub-path; neighboring sub-paths were never released concurrently. The totals counted sources whose flows reached the road, rather than independent avalanche events. The 208 sub-paths belong to 71 catchments. In most catchments containing several road-reaching sub-paths, all of these sub-paths reached the same road kilometer. *Change:* Sect. 3.7 will clarify what the counts represent; Sect. 4.4 will give rankings by catchment as well as by sub-path; Sect. 5.2.3 will express path density in terms of catchments; Sect. 5.3 will describe how prescribed polygons constrain the representation of multi-branch release.

R2.12 *"McClung reports an empirical relationship between mean slab density and thickness, $\rho \approx 225D^{0.24}$ kg m⁻³, with considerable scatter. Thus, fracture depth and density are not necessarily independent variables."*

For all 208 polygons, substituting the prescribed fracture depths into this relationship gave densities of 126 to 299 kg m⁻³, with scenario medians spanning 207 to 244 kg m⁻³. The fixed value of 250 kg m⁻³ was within the range for individual polygons and higher than the scenario medians. Our sensitivity analysis spanned 100 to 400 kg m⁻³, encompassing all these densities. Changing density had little effect on reach, whereas pressure varied proportionally. *Change:* Sect. 3.2 will report this comparison and state that the relationship was derived for dry slabs.

4. Storm history, snow state and flow regime

R2.13 *"However, $\Delta H S 3$ is not a physical description of the meteorological and snowpack history that produces a large avalanche."*

We will explain in Sects. 3.1 and 5.3 that using a three-day snow-height increase with a specified return period to prescribe release depth follows an engineering convention and does not reconstruct weather or snowpack history. We will also note that national practices, for example in Switzerland and Austria, treat this convention differently. Recorded conditions illustrated the distinction: a snow pit examined on the 2022 event date revealed failure on buried surface hoar, and both 2018 events followed substantial warming. We will keep the convention because it is compatible with the corridor data available. In the revised manuscript, Sects. 3.1 and 3.2 will bring the three-day definition into agreement with the earlier engineering study's storm durations (2, 2.5 and 3 days) and amend the reference depths (#10 in Part 1). *Change:* Sects. 3.1, 3.2 and 5.3.

R2.14 *"It is therefore impossible to know whether the fitted variation in μ primarily reflects volume or whether it is absorbing differences in snow temperature, moisture, fragmentation, entrainment, flow regime and path characteristics."*

The four documented events included one full-depth wet avalanche, one small dry release accompanied by a powder component, and two releases associated with warming. With one fitted friction value per event, a dense-flow model cannot disentangle the effects listed in the comment. The events nevertheless supported separate wet and dry lines: on the Campanario path, even with the erodible layer, $\mu \geq 0.24$ stopped the 2022 flow above the road (Fig. R3d), whereas the wet line assigns 0.27 at its volume. We will explain that the four events supported this separation but no finer distinction in snow state. A new discussion item, "Snow state and flow regime", will clarify in Sect. 5.3 that our simulations modeled dense flow alone and that fitted friction incorporated the differences among these events. *Change:* Sect. 5.3.

R2.15 *"A rare avalanche scenario should represent a physically coherent extreme event, not simply a larger fracture depth applied to an otherwise unchanged conceptual snowpack."*

For the Extreme scenario, we raised the released mass without changing the conceptual snowpack, snow state or flow regime. Section 3.1 will set out this definition, and Sect. 5.3 will discuss its limitation. The dry line assigned its lower bound of 0.155 to every release exceeding about 18 000 m³, accounting for 439 of the 624 simulations. We used this line to explore one direction of uncertainty; its results will form the upper envelope reported for exposure. *Change:* Sects. 3.1 and 5.3.

R2.16 *"The use of AvaFrame, its open-source character, and the application to a poorly studied Chilean corridor are useful, but these aspects do not in themselves constitute a scientific advance." and "PRA $\rightarrow P(D, L, B, \rho, T, \dots) \rightarrow$ entrainable snow $\rightarrow$ flow regime $\rightarrow$ dynamic simulation"*

These features alone do not amount to a scientific advance. We accept the referee's point and will adjust the introduction to avoid presenting them as such. The contribution is a corridor-scale exposure assessment covering 208 release areas along the road, supported by local calibration, reproducible calculations and openly available data and open-source software. By comparison, the earlier engineering study ran dynamic simulations for 29 release areas in seven zones. We support the direction of the framework proposed by the referee; our outlook will present it as a natural next step. Available data for the corridor are insufficient for this development (see below). *Change:* Sects. 1, 5.3 and 6.

Limits of the revision and summary of changes

What this revision cannot do

- Calibrate release probabilities: a catalog recording avalanche occurrence for individual storms is unavailable, so release probability will remain a parameter of the risk estimate (R1.1).
- Establish statistical distributions for release dimensions: a catalog containing these dimensions is unavailable (R2.10, R2.16).
- Recalibrate wind factors or collect observations of snowpack conditions and erodible snow along avalanche paths: station records in the corridor are short and incomplete, and snowpack observations are sparse (R1.1, R2.16).
- Use deposit volume in the 2011 calibration: no measured value exists (R2.2).

Summary of the planned changes to the manuscript

- Framing: define the scope as a deterministic corridor-scale exposure assessment, removing claims that exceed it (Part 2).
- Friction: introduce a smooth law relating effective friction to volume, with wet and dry lines calibrated using three of the four events and AIMEC, and the fourth serving as a check; give a band of results by kilometer; propose a base case using the wet line, with the dry line defining the upper envelope (R1.2, R2.1 to R2.4).
- Calibration and validation: document the acceptance criteria and the trade-off between volume and friction for Campanario 2011; rewrite the assessment of Campanario 2022; amend the reference simulation's reported values and the events' roles in Tables 1 and 2 (#19, #28, R2.2, R2.4).
- Comparison with earlier studies: present the Chilean studies as a qualitative check and rewrite the comparison with the earlier engineering study (R2.5, R2.6).
- Entrainment: report the comparison's main findings in Sect. 5.3 and provide an appendix containing the figures (R2.7, R2.8).
- Risk: extend Sect. 4 with a short subsection estimating individual risk to first order, and revise the statements on annualized risk in the abstract and Sect. 5.3 (R1.1).
- Methods and data: correct errors or fill gaps in the road-reaching criterion and pressure classes; the wind and slope factors; reference depths and the gradient with elevation; criteria used to delineate release areas; release volume, geometry and density; the A11-1 fracture depth; and the definition of road-reaching counts, with rankings by catchment (R1.1, #1 to #26, R2.10 to R2.12).
- Limitations and outlook: broaden the discussion to include release geometry and multi-branch releases, snow state and flow regime, the convention based on a three-day snow increase, DEM resolution and the boundaries of the sensitivity analysis; recommend event documentation in place of establishing an instrumented test site (R2.9 to R2.16, #32, #33, #35).
- Figures and references: refine Figs. 1, 3, 4, 5 and 6 (#5, #29, #30, #34; R1.2); incorporate additional references (McClung and Schaerer, 1993; McClung, 2009; Bühler et al., 2011; Wirbel et al., 2026; Buser and Frutiger, 1980; Gruber and Bartelt, 2007; Vera Valero et al., 2015; the 2022 snow-pit report) and amend the entries noted by RC1 (#36, #37).

Iván Latorre, on behalf of all co-authors