

Higher road-traffic mortality on warm days in Thailand: a nationwide time-stratified case-crossover study, 2011–2025

Fabio Luiz Vieira

`fabio.vieira16@alumni.imperial.ac.uk`

My Brazilian Doctor <https://orcid.org/0000-0003-2711-2769>

Research Article

Keywords: ambient temperature, road-traffic injury, case-crossover, heat–health warning systems, Thailand, motorcyclists

Posted Date: October 5th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11226575/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: The authors declare no competing interests.

Higher road-traffic mortality on warm days in Thailand: a nationwide time-stratified case-crossover study, 2011–2025

Fábio Luiz Vieira, MD, MSc¹

¹ *My Brazilian Doctor, São Paulo, Brazil*

ORCID 0000-0003-2711-2769

Running head: Temperature and road-traffic mortality in Thailand

Corresponding author: Fábio Luiz Vieira, MD, MSc · My Brazilian Doctor, São Paulo, SP, Brazil ·
fabio.vieira16@alumni.imperial.ac.uk · ORCID 0000-0003-2711-2769

Word count (main text): 5,645 words (excluding abstract, tables and references)

Tables: 5

Figures: 3

Supplementary files: S1-S5

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Competing interests

The author declares no competing interests.

Data availability

The road-traffic death records (RTDDI) are publicly available from the Thailand Open Government Data portal (<https://data.go.th/dataset/rtdi>) under CC-BY. The exposure dataset constructed for this study (4,514,684 daily observations from 1,347 harmonised weather stations and a 0.1-degree gridded reconstruction of daily maximum temperature), the analytic panels and the complete analysis code,

including the conditional Poisson estimator, are published and publicly accessible on Zenodo:
<https://zenodo.org/records/22929210> (doi:10.5281/zenodo.22929209).

Declaration of generative AI and AI-assisted technologies

During the preparation of this work the author used Claude (Anthropic), a generative AI tool, to assist with writing and debugging the analysis code and with drafting and language editing of the manuscript, and ChatGPT (OpenAI) to support review and revision of the manuscript. The study was conceived, conducted and reviewed by the author, who made all decisions on design, analysis and interpretation, verified all code, numerical results and text, and takes full responsibility for the content of the publication. The AI tools are not authors.

Ethics

This study used exclusively de-identified data obtained from publicly accessible data sources. The RTDDI road-traffic death dataset is openly available through the Thailand Open Government Data portal. No participants were contacted and no identifiable personal information was accessed. Ethical approval and informed consent were therefore not required for this secondary analysis of openly available data.

Abstract

Background. This study examines the association between ambient temperature and road-traffic mortality across Thailand and characterises its pattern: the shape of the association over the local temperature distribution, and the share of the associated deaths that arises on moderately warm rather than extreme days. Temperature–mortality research has concentrated on non-accidental causes. Recent work in Latin America, Japan and China has quantified heat effects on road-traffic and other external-cause deaths, but nationwide evidence from Southeast Asia remains scarce, and few studies report where across the temperature distribution the associated burden accrues.

Methods. We analysed 283,847 road-traffic deaths in Thailand's 77 provinces between 1 January 2011 and 24 August 2025, from the integrated RTDDI death file. The exposure dataset was constructed for this study: 4,514,684 daily station observations from 1,347 stations, harmonised from two national meteorological networks with per-station quality control, and a 0.1° gridded reconstruction of daily maximum temperature by inverse-distance weighting from 1,145 stations. Exposure entered as province-specific percentile bands. We fitted a time-stratified case-crossover design as a conditional Poisson model, stratifying on province $\times$ year $\times$ month $\times$ day-of-week, with cluster-robust variance on province, adjusting for precipitation and the Songkran and New Year holiday periods; the estimator was implemented for this study and validated against a Poisson GLM with dense stratum fixed effects (agreement to 5.8×10^{-15}). Five pre-specified sensitivity analyses addressed spatial exposure resolution, exposure assigned by crash rather than death date, exclusion of the Songkran window, consecutive-day heatwave definitions, and composite humid-heat metrics.

Results. Mortality risk per day rose from the cold end of the distribution to approximately the 75th local percentile and showed no further increase above it (P75–90 RR 1.045, 95% CI 1.023–1.068; P95–99 RR 1.050, 1.018–1.083; $\geq$ P99 RR 1.041, 0.979–1.108; reference P40–60). A binary extreme-heat-day contrast gave RR 1.015 (0.992–1.039), because its comparison group already contains the elevated warm days. The shape persisted when exposure was reassigned at 0.1° spatial resolution using crash coordinates on the identical 107,313 geocoded deaths, despite a mean absolute difference of 2.95 °C between the two exposure measures, and when exposure was assigned by crash date rather than death date in the 94,437 deaths where both were available. It was also unchanged by excluding the Songkran holiday period, by a consecutive-day heatwave framing across 15 definitions, and by substituting composite humid-heat indices for dry-bulb temperature. Excess mortality associated with temperatures above the P40–60 reference band was 4,509 deaths (95% CI 2,581–6,442), 1.59% of all road-traffic deaths. **Approximately 72% of that excess occurred between the 60th and 90th percentiles, whereas only 14.8% occurred above the 95th percentile.**

Conclusions. Road-traffic mortality was higher on warm days than on days of median temperature, with risk rising from moderately warm temperatures onward and levelling off above approximately the 75th local percentile. Because moderately warm days are common, they carried most of the temperature-associated excess: about 72% arose between the 60th and 90th percentiles and 14.8% above the 95th. Warm weather therefore warrants sustained road-safety attention across the whole warm season, and not only on the extreme days that heat–health alert systems are designed to detect, which account for a small share of this burden.

Keywords: ambient temperature; road-traffic injury; case-crossover; heat–health warning systems; Thailand; motorcyclists.

1. Introduction

Road-traffic injury kills about 1.25 million people a year worldwide and is among the leading causes of death in the WHO Western Pacific Region. Injuries as a whole accounted for roughly 249 million disability-adjusted life-years in 2019.

Until recently, environmental epidemiology largely bypassed this burden. The dominant temperature–mortality literature is about non-accidental causes, a gap stated independently by several groups: few studies had examined temperature and external causes of death (Pan *et al.* 2022); most previous work addressed non-accidental morbidity or mortality, with far less on heat-related accidental events (He *et al.* 2023); the association and burden of heatwaves on mechanism-specific injury mortality remained underexplored (Hu *et al.* 2025); and few nationwide studies had quantified temperature-related risk and burden for cause-specific injury (Zhou *et al.* 2024).

That gap has narrowed. Between 2022 and 2025 it was addressed for Japan, for China, and — with a 272-city study covering six countries — for Latin America (Hsu *et al.* 2025). A systematic review and meta-analysis of 34 high-temperature effect estimates (Liang *et al.* 2022) established that the association is real but modest: pooled relative risk 1.025 (95% CI 1.014–1.035) for road-traffic accidents and 1.073 (1.065–1.091) for traffic-accident injuries, with 1.114 (1.092–1.137) in the mortality subgroup.

Several mechanisms have been proposed: prolonged heat exposure on the road; vehicle mechanical failure; pavement deterioration; increased traffic volume; emergency services under strain, with more calls and longer response times; and behavioural change, including impaired attention and riskier driving. Motorcyclists, cyclists and pedestrians have been argued to be particularly susceptible, lacking protective enclosures.

Global burden analyses have gone further, attributing a measurable proportion of road-injury mortality and disability to high, low and non-optimum temperatures, with substantial geographic and socioeconomic heterogeneity (Cui *et al.* 2023). Such aggregate estimates answer how much burden is attributable to temperature. They do not establish **where along the local temperature range** that burden actually occurs.

Three questions motivate this study.

First, evidence from Southeast Asia remains scarce, and road-traffic mortality is absent from it. None of the 34 effect estimates pooled by Liang *et al.* (2022) came from Southeast Asia; their regional subgroups were Europe, Asia — represented by China, Korea, Taiwan, Japan and Iran — and the USA. A 2026 scoping review of heat-related health impacts across the ten ASEAN countries (Aung *et al.* 2026) makes the gap more precise. It screened 851 studies and included 76, of which 20 involved Thailand — the joint highest of any member state, alongside Vietnam — so the Thai heat–health literature is comparatively well developed. Yet among the 28 heat-related **mortality** studies in the region, the outcomes examined were all-cause (n = 19), cardiovascular (n = 9), respiratory (n = 9), diabetes, malignancy, genitourinary, COVID-19 and intestinal infection. For Thailand specifically the review records all-cause, cardiovascular, respiratory, diabetes, genitourinary and neoplasm mortality. **Road-traffic mortality does not appear as a studied outcome, in Thailand or anywhere else in the region.** Injury enters the regional literature only as morbidity, through 39,313 emergency injury visits across 733 facilities in Hanoi (Le *et al.* 2024). The review's design profile is also relevant: of the 28 mortality studies, 15 were time-series and only 2 used a case-crossover design, and few were nationwide, the majority being provincial or multi-provincial.

Regional work on road traffic specifically is limited in scope. The one directly comparable study analysed 42,989 injury-causing road-traffic accidents in Singapore between January 2016 and November 2021 using a time-stratified case-crossover design; it found **cooler** temperatures (adjusted OR at 25 °C 1.087, 1.023–1.156) and higher rainfall (adjusted OR at 38 mm 1.168, 1.129–1.208) associated with increased odds, with stronger effects on expressways (Chua *et al.* 2025). Its outcome is accident occurrence rather than mortality, and Singapore is an equatorial city-state with a very narrow thermal range. Thailand has one of the world's highest road-death rates and a vehicle fleet dominated by motorcycles, and the Latin American authors identify the tropical Global South as the priority gap. Whether ambient temperature is associated with road-traffic mortality in Thailand, and where within the temperature distribution any associated burden occurs, therefore remains unclear.

Second, few studies have examined where across the temperature distribution the associated road-traffic mortality burden accrues. Attributable fractions are reported as totals, and none of the studies pooled by Liang *et al.* (2022) reported one at all. Whether the associated excess falls on the extreme days that a heat–health warning system is designed to detect, or accumulates across ordinary warm days, is a different question from whether an association exists, and it bears directly on whether threshold-based instruments are well matched to the problem.

Third, published estimates are difficult to compare. Reported heat relative risks across four studies range from 1.05 to 1.60, but the four use four different reference temperatures, from the 1st percentile to –12.1 °C. Differences in reference temperature account for an important component of this apparent between-study variation.

These questions call for a different design from the one that produced the existing global estimates. Whereas previous global burden analyses have quantified temporal trends in **modelled** road-injury burden attributable to non-optimum temperatures, the present study estimates **short-term daily mortality associations with observed temperature**, allowing the exposure–response curve and the distribution of excess deaths across the local temperature range to be characterised.

2. Methods

2.1 Outcome

Deaths came from the RTDDI integrated road-traffic death file (data.go.th/dataset/rtddi, CC-BY), which merges Ministry of Public Health injury surveillance, Royal Thai Police records, and Road Accident Victims Protection e-claim data. Of 296,459 records, 283,847 fell within the analysis window (1 January 2011 – 24 August 2025, the end bounded by the retirement of NOAA GSOD) and matched a province-day with valid exposure: 77 provinces and 5,340 days with valid matched exposure data, out of 5,350 calendar days in the window.

Geography is **province of death**, which is 100% complete. Province of residence was rejected: it is 0–52% complete depending on year.

2.2 Exposure

Province daily maximum temperature from the Thai Meteorological Department synoptic network via NOAA GSOD. Sixty-four provinces contain at least one station; the remaining 13 were assigned the nearest station using province centroids from HII telemetry coordinates (12 of 13 within 71 km; Bueng Kan 109 km). Precipitation (GSOD _{PRCP}, province daily mean) was carried as a confounder.

173 Temperature was entered as **province-specific percentile bands** (<P5, P5–25, P25–40, **P40–60**
174 = **reference**, P60–75, P75–90, P90–95, P95–99, ≥P99), because 36 °C is routine in Ubon
175 Ratchathani and extreme in Phuket, and as a continuous deviation from the province median.
176 Lags examined were same-day, mean of lag 0–1, and mean of lag 0–3.

177 **2.3 Design and estimation**

178 **Time-stratified case-crossover, fitted as conditional Poisson**, with stratum = province × year ×
179 month × day-of-week. Conditioning on the within-stratum total reduces the Poisson likelihood to
180 a multinomial logit over the days of the stratum:

$$181 \quad LL = \sum_s [\sum_i y_i \cdot \eta_i - N_s \cdot \log \sum_i \exp(\eta_i)]$$

182 fitted by Newton–Raphson with analytic gradient and Hessian (`Analysis/condpois.py`). The
183 estimator was **validated against a statsmodels Poisson GLM with dense stratum fixed**
184 **effects**: coefficients agree to 5.8×10^{-15} .

185 By construction the design controls province, season, long-term trend and day-of-week; only
186 day-to-day variation *within* a province-month-weekday cell identifies the association. Variance is
187 **cluster-robust on province** (77 clusters); model-based standard errors were 1.14–2.0 times too
188 narrow because daily counts are serially correlated within province.

189 **2.4 Confounders requiring explicit handling**

190 **Songkran**. Thailand's two road-death peaks are Songkran (11–17 April) and New Year (29
191 December – 4 January), the "seven dangerous days". Songkran falls at the annual temperature
192 peak, so month-level stratification does not remove it: within April, Songkran days average 36.1
193 °C and 0.889 deaths per province-day against 35.9 °C and 0.676 on the rest of April. Both
194 windows enter as indicators.

Precipitation. A hot tropical day is largely a rainless day, and rain changes both crash risk and traffic volume. Models are reported with and without rain terms (rain ≥ 1 mm, heavy rain ≥ 20 mm, $\log(1+\text{mm})$).

2.5 Secondary analyses

- **Spatial exposure resolution.** Crash coordinates were binned to 0.1° cells and daily Tmax interpolated by inverse-distance weighting (power 2, 30 km radius) from 1,145 TMD/GSOD and HII stations, then the case-crossover re-run on the *identical* deaths with strata redefined on cells. Median cell-to-station distance 10.3 km (7.0 km weighted by deaths).
- **Humid heat.** RH at the hottest hour estimated as $e(Td_{\text{mean}}) / e_s(T_{\text{max}})$ (Magnus formula, Alduchov–Eskridge coefficients), then NWS Rothfus heat index, Steadman apparent temperature and Stull wet-bulb compared against dry-bulb Tmax on the same rows and strata, so conditional log-likelihoods are comparable. Effect modification tested by nested likelihood-ratio test (2 df).
- **Heatwaves.** Fifteen definitions (thresholds P90, P92.5, P95, P97.5, P99 $\times$ minimum durations 2, 3, 4 days), distinguishing the **total effect** from the **added effect** of persistence net of the day's own temperature (Gasparri & Armstrong 2011).
- **Holiday exclusion.** Songkran is both the annual temperature peak and a large mortality spike, so in addition to adjusting for it the analysis was repeated with the 11–17 April window removed entirely (7,168 deaths, 2.53% of the total), and again with New Year removed as well. Constant indicator columns were dropped from those models.
- **Crash-date exposure.** See Section 2.7.

- **Reference-scale comparability.** For cross-study comparison, the identical model was refitted with the minimum-risk band (<P5) as the omitted category, so confidence intervals derive from the same cluster-robust covariance rather than from dividing point estimates.

2.6 Excess-mortality estimand

We report **excess deaths associated with temperatures above the P40–60 reference band**, computed as $\sum_b n_b (1 - 1/RR_b)$ over bands b with $RR_b > 1$, where n_b is the observed number of deaths in band b . Confidence intervals are Monte-Carlo draws (8,000) from the **full cluster-robust covariance** of the band coefficients, which are correlated.

Three properties of this estimand are stated explicitly because they affect interpretation and are not interchangeable with the conventional heat-attributable burden:

1. It is defined **against the P40–60 reference band**, not against a minimum-mortality temperature. It therefore answers: how many more deaths occurred in the bands above the reference band than would be expected had those days carried the risk of the P40–60 band?
2. It is **one-sided**: bands with $RR < 1$ contribute zero rather than a negative quantity. The corresponding two-sided (net) quantity is reported alongside it.
3. It is consequently **not comparable** to published attributable fractions anchored at a minimum-mortality temperature without recomputation, which we provide (Section 3.4).

2.7 Crash-date exposure and the crash-to-death interval

`DateRec` (วันที่เกิดเหตุ, e-claim) is the crash date per the official dictionary and `DeadDate` the date of death. The principal analysis was refitted twice on the same 94,437 individuals, assigning exposure by death date and by crash date, to quantify exposure-date misclassification directly.

Two exclusions. **The 2561 (2018) file was dropped entirely**: its crash-to-death interval is symmetric over ± 320 days (SD 145 days; 61% beyond ± 60 days) against SD 10 days and 0.5% in the adjacent 2562 file, and reversing day/month does not repair it — row misalignment or a corrupted column, not a date-format problem. Negative intervals (1.11%) and intervals beyond the 30-day RTDDI definition (1.21%) were also dropped.

`DateRec` originates in the compulsory motor-insurance e-claim subsystem, so records carrying a crash date are those matched to a claim: the subset is 53% motorcycle against 41% in the full file and is not representative. Analyses of the crash-to-death interval itself are reported in Supplementary Material S3.

2.8 Software and use of AI-assisted tools

All analyses were run in Python. A generative AI tool (Claude, Anthropic) was used, under the author's direction, to assist with writing and debugging the analysis code and with drafting and language editing of the text; a second tool (ChatGPT, OpenAI) was used to support review and revision of the manuscript. The study question, design, analytic decisions and interpretation are the author's; the author reviewed and verified all code, numerical results and text. The exposure dataset, the analytic panels and the complete analysis code are openly available (Vieira 2026).

3. Results

3.1 The association is graded and does not increase beyond the 75th percentile

No binary extreme-heat definition isolated an excess (Table 1): $\geq P95$ RR 1.015 (0.992–1.039); $\geq P99$ RR 1.006 (0.953–1.063); the lag 0–1 and lag 0–3 means were similar.

The graded model shows why (Table 2, Figure 2). Risk per day rose from the cold end of the distribution to about the 75th local percentile. Against the P40–60 reference, RR reached 1.045

(1.023–1.068) at P75–90, and **we found no evidence that risk continued to increase beyond this point:** 1.044 (1.015–1.073) at P90–95, 1.050 (1.018–1.083) at P95–99, and 1.041 (0.979–1.108) at $\geq$ P99. The continuous estimate was **RR 1.0127 (95% CI 1.0103–1.0152) per 1 °C increase in Tmax, centred at the province-specific median.**

These contrasts are uninformative about heat by construction, not because heat is unrelated to road deaths: the comparison group — every day below P95 — already contains the elevated P60–90 days that carry most of the excess. A binary threshold compares warm days with a mixture that is itself partly warm.

Within the exposed-user group, where power is greatest, no heat band exceeded P75–90 (P90–95 vs P75–90 ratio 0.992, $p = 0.72$; P95–99 vs P75–90 1.028, $p = 0.27$; $\geq$ P99 vs P75–90 0.989, $p = 0.81$). The same held on the absolute scale: against 34–36 °C, 36–38 °C gave 1.023 (0.990–1.058), 38–40 °C gave 1.047 (1.002–1.093), and ≥ 40 °C gave 1.002 (0.909–1.103).

3.2 The shape persists under fine spatial exposure assignment

Spatial exposure misclassification of Berkson type was the leading candidate explanation for the flattening, and was examined directly by reassigning exposure at the crash site.

On the same 107,313 geocoded deaths, the cell-level and province-level exposures differ substantially — correlation 0.752, **mean absolute difference 2.95 °C** — yet the two exposure–response curves were indistinguishable (Table 3, Figure 3), and the flattening persisted at cell level (P90–95 vs P75–90 ratio 1.021, $p = 0.41$; P95–99 vs P75–90 1.019, $p = 0.49$; $\geq$ P99 vs P75–90 0.952, $p = 0.28$). This substantial refinement in spatial exposure resolution left the shape unchanged, **making spatial exposure misclassification an unlikely explanation for the observed plateau.** Liang *et al.* (2022) identify coarse spatial and temporal exposure assignment

as a shortcoming of this field as a whole and call for work at a finer scale; this analysis provides that test directly.

The geocoded subsample did show larger RRs than the full sample (≈ 1.08 versus ≈ 1.05 at P90–99) — but so did the province-level model fitted on those same deaths. The difference is **composition, not resolution**: geocoding is far more complete for motorcycle deaths (69.9%) than for car occupants (30.5%) or pedestrians (26.7%).

3.3 Neither persistence nor humidity accounts for the shape

Heatwaves. All 15 definitions gave null total effects; the largest was P97.5/ ≥ 3 days at 1.030 (0.982–1.080). Under the Hu *et al.* definition (≥ 2 consecutive days above P92.5) the total effect was 1.003 (0.980–1.028). The **added** effect of persistence, net of the day's own temperature, was ≈ 0.96 and consistent across three adjustments — at or slightly below unity. There was no duration–response (day 1 RR 0.998, day 2 1.012, day 3 0.992, day 4+ 1.005). Full grid in Supplementary Table S2.

Humid heat. Composite humid-heat indices did not improve model fit over Tmax (Δ conditional log-likelihood –26.0 heat index, –23.3 apparent temperature, –47.6 wet-bulb), and there was no evidence of temperature–humidity interaction ($p = 0.23$ – 0.56 across three humidity measures). Humidity itself showed an **inverse independent association** with road-traffic mortality (dewpoint RR 0.976, 0.968–0.984), and adjusting for it left the exposure–response shape and the burden distribution unchanged. The per-degree estimate was larger in the wet season (1.0223) than the dry (1.0080); part of this reflects the narrower wet-season temperature distribution (SD 2.39 vs 3.25 °C), and standardising to one province-SD reduced the excess-risk ratio from $2.8\times$ to $1.7\times$. A residual seasonal difference remains unexplained. Detail in Supplementary Material S1.

3.4 Most of the associated excess occurs below extreme-heat thresholds

Excess mortality associated with temperatures above the P40–60 reference band was **4,509 deaths (95% CI 2,581–6,442) over 14.6 years = 1.59% (0.91–2.27%) of all road-traffic deaths**, about 308 per year.

The distribution across bands is the substantive result (Table 4, Figure 1). **Only 665 of 4,509 deaths — 14.8% — fell in the P95+ bands.** Seventy-two per cent accrued in the P60–90 bands, reflecting the combination of elevated relative risks and the much greater frequency of these moderately warm days.

Three sensitivity analyses of the estimand (Section 2.6):

Estimand	Excess deaths	95% CI	Share in P95+
vs P40–60, one-sided (reported)	4,509	2,581–6,442	14.8%
vs P40–60, net of cooler-day deficit	1,325	–1,848 to 4,436	—
vs minimum-risk band <P5, one-sided	15,454	9,177–21,918	8.8%

Two points follow. The **magnitude** of the excess is strongly dependent on the reference band, ranging from 1.59% to 5.44% of all deaths, and the net quantity relative to the P40–60 band is not distinguishable from zero — warm-day excess is largely offset by a cool-day deficit. The **distribution**, however, is robust: the share occurring above P95 was 14.8% using P40–60 as reference and 8.8% using the minimum-risk band. Adjusting for humidity gives 4,175 deaths (1.62%) with 15% in P95+ bands.

3.5 Design validation

The model recovered the expected elevation in mortality during Thailand's two established high-risk road-safety periods: Songkran RR 1.311 (95% CI 1.241–1.384) and New Year RR 1.194 (1.140–1.252).

324 Excluding the Songkran window entirely, rather than adjusting for it, left the exposure–response
325 curve unchanged: P75–90 RR 1.046 (1.024–1.069) against 1.045 in the main model, P95–99
326 1.050 (1.016–1.084) against 1.050, and the contrasts against P75–90 remained null (P90–95 $p =$
327 0.48; P95–99 $p = 0.87$; $\geq P99$ $p = 0.76$). Supplementary Material S5.

328 **3.6 Exposure assigned by crash date gives the same shape**

329 Because crash dates are unavailable after 2021, the main analysis uses date of death. Refitting on
330 the same 94,437 individuals under both assignments (Table 5) showed no attenuation: death-date
331 point estimates were if anything slightly higher, with overlapping intervals throughout, and the
332 shape — rise to P75–90, then no further increase — was preserved under both. With 76.7% of
333 deaths occurring the same day and temperature strongly autocorrelated, the two assignments
334 largely coincide.

335 In the same subset, higher crash-day temperature was **not** associated with a shorter crash-to-
336 death interval (adjusted OR for same-day death 0.998 per +1 °C, 0.989–1.006, $p = 0.62$).
337 Supplementary Material S3.

338 **3.7 Comparison on a common reference scale**

339 Refitting against the minimum-risk band moves the all-deaths P95–99 estimate from 1.050 to
340 1.106 (1.062–1.151), against 1.16 in Latin America. By road-user type, our **motorcyclist**
341 estimate — 1.193 (1.126–1.265) at P95–99 — is close to the 1.24 reported at P95 for Latin
342 American motorcyclists. Our estimate for **enclosed-vehicle occupants** shows no association at
343 any band (P95–99 1.025, 0.928–1.131), where Latin America reports 1.14. Full table in
344 Supplementary Table S4.

Comparisons with Hsu *et al.* are restricted to point estimates because a published Author Correction identified an error in the confidence intervals reported in their Table 2; point estimates and study conclusions were unaffected.

4. Discussion

4.1 Principal findings

In this hot tropical setting, ambient temperature was associated with road-traffic mortality per day, but we found no evidence that risk continued to increase above approximately the 75th local percentile. The gradient below that point is precise and robust; it is the absence of further rise above it, together with the resulting distribution of the associated excess, that constitutes the contribution.

Four analyses that might have accounted for the flattening did not. It persisted under substantially finer spatial exposure assignment on identical deaths, making spatial misclassification an unlikely explanation — and note that Hsu *et al.* attribute the taper they observe on the absolute scale to sparse data at the extremes. It persisted under a consecutive-day heatwave framing across 15 definitions, under substitution of humid-heat indices for dry-bulb temperature, and under exposure assigned by crash date rather than date of death.

4.2 Behavioural and exposure pathways

The shape we observe — a rise beginning at moderately warm temperatures that does not continue into the extremes — is difficult to reconcile with a purely physiological account, and the existing literature offers a plausible behavioural pathway that could contribute to this pattern. Pan *et al.* (2022) argue that associations between temperature and external causes of death may be strongly influenced by human behaviour, invoking this to explain why their lag–response

patterns were shorter than those typical for non-accidental mortality. They note that people engage in more outdoor activities in warmer conditions and that, for transport specifically, driving performance deteriorates at warm temperatures. In their Japanese data the transport-mortality relation increased **monotonically** across the temperature range (RR 1.60, 95% CI 1.35–1.90 for heat), which is a useful contrast with the plateau we observe (Section 4.3). Zhou *et al.* (2024) make a closely related argument for injury hospitalisations: alongside thermal discomfort and its consequences for fatigue, concentration and judgement, they propose that **under moderate heat conditions people tend to have more outdoor activities, thereby increasing the likelihood of injury.**

Both components fit what we observe. A mechanism operating through greater mobility and outdoor activity could engage at moderately warm temperatures rather than require extreme heat, which is where our association begins; and one operating through degraded driving performance could plausibly affect all road users rather than only those without protective enclosure, consistent with our finding that exposed and enclosed users are not distinguishable in any heat band (Section 4.3). The increase from moderately warm temperatures onward may therefore partly reflect changes in population exposure and behaviour, not only physiology.

The plateau invites the complementary hypothesis: that at the upper end of the Thai temperature distribution, behavioural adaptation or reduced exposure offsets any further increase in per-trip risk, so that risk per day stops rising. **We state this explicitly as a hypothesis generated by the present findings, not as an inference from the cited work.** Neither Pan *et al.* nor Zhou *et al.* examined whether mobility declines under extreme heat, and neither should be read as evidence that it does; their contribution here is to establish that behaviour is a plausible and probably important pathway for temperature and external causes generally. Testing the hypothesis requires

mobility or traffic-volume data, which we did not have — the same gap identified in Section 4.5, where we note that a within-stratum decline in circulation on the hottest days would produce exactly this pattern.

The closest external evidence on shape comes from the one injury study in the region. In Hanoi, Le *et al.* (2024) modelled 39,313 emergency injury visits against daily mean temperature (range 10.6–38.5 °C) and found a curve referenced at 15 °C peaking at **33 °C** (RR 1.3, 1.2–1.6); among males, it "increases to 33 °C, at which point the association decreases in an inverted U-shape response", with 33 °C well inside their observed range rather than at its edge. That is an interior maximum followed by decline, in a tropical Southeast Asian city, for an injury outcome — the nearest independent parallel to the shape we report. Three differences limit it: their outcome is emergency-visit **morbidity**, not mortality; their 33 °C is a daily **mean** and not comparable to our 35.5 °C daily maximum; and their female curve instead reached its highest value at the highest temperatures, with intervals the authors flag as imprecise.

The other tropical road-traffic case-crossover points the opposite way: in Singapore, Chua *et al.* (2025) report higher odds of injury-causing accidents at **cooler** temperatures and with higher rainfall. Their outcome is accident occurrence rather than death, and Singapore is equatorial, with a thermal range narrow enough that cool days are largely rainy days, making temperature and rainfall difficult to separate. Thailand spans a much wider range with a distinct dry season, and our precipitation terms were themselves null while the temperature gradient persisted. The divergence plausibly reflects outcome definition and the confounding structure of an equatorial climate rather than a contradiction about heat.

Non-linear temperature–health relationships are also the norm rather than the exception in this region: the ASEAN scoping review reports J-shaped, U-shaped, V-shaped, M-shaped and

inverse-S-shaped associations across outcomes and countries, with the shape varying by outcome and setting (Aung *et al.* 2026). A departure from monotonicity in Thai data is therefore not anomalous in regional terms.

Behavioural avoidance of outdoor heat is documented there as a regional phenomenon rather than a speculative one: the review invokes "behavioural change during extreme heat days, such as spending time indoor and air-conditioning" to explain null findings in ASEAN studies. That is offered in the context of effect modification by air pollution rather than of curve shape, and neither the review nor the studies it summarises examined travel behaviour, so it supports the plausibility of the pathway and not the specific claim that reduced mobility explains our plateau. Flattening is also not unprecedented even where the overall relation is not flat: Zhou *et al.*'s total-injury curve was approximately linear, but the curve for head and neck injuries **became constant in high temperature ranges**. None of this displaces the central interpretation. Whether the operative mechanism is behavioural, physiological or a combination, the association we document is one of warm weather rather than extreme heat.

Pan *et al.*, Zhou *et al.* and Le *et al.* all use daily **mean** temperature, whereas we use daily **maximum**, so absolute temperatures are not comparable across these studies — a further reason to compare on the percentile scale.

4.3 Relation to published estimates

Our estimates are closely in line with the pooled literature. The meta-analysis of Liang *et al.* (2022) reports a pooled relative risk of **1.050 (1.017–1.084)** for high temperature versus a reference temperature in traffic-accident-injury studies — essentially identical to our P95–99 estimate of 1.050 (1.018–1.083) — and a pooled per-degree estimate of 1.008 (1.001–1.021) for road-traffic accidents, within which our 1.0127 (1.0103–1.0152) per +1 °C falls. This reframes

the comparison that follows: relative to the body of published evidence, it is the Latin American estimate of 1.16 that lies above the pooled value, not ours that lies below it.

Read at face value, our P95–99 RR of 1.050 is well below the 1.16 reported for Latin America. Much of that difference is attributable to reference choice: our estimate is anchored at the median band and theirs at the minimum-mortality percentile. Placed on a common scale, our motorcyclist estimate is consistent with theirs. More generally, differences in reference temperature account for an important component of the apparent between-study variation in effect estimates across this literature, and comparisons of raw relative risks across studies should be interpreted with that in mind.

Two differences survive re-referencing.

Shape. We observed no increase above P75; Hsu *et al.* report a monotonic rise on the percentile scale, Pan *et al.* a monotonic transport-mortality relation in Japan, and Zhou *et al.* an approximately linear one in China. Japan and China are temperate settings with considerably greater thermal range. Notably, Hsu *et al.*'s own hottest climate cluster is itself flat, at 1.16 at both P95 and P99. We therefore offer a hypothesis rather than a contradiction: one possibility is that **saturation is more likely to emerge in hot tropical environments**, where the upper tail represents a smaller departure from an already high thermal baseline. Indirect support comes from He *et al.*, who found road traffic had the smallest projected increment among accidental causes under warming, and from the meta-analytic subgroup analysis of Liang *et al.* (2022): among traffic-accident-injury studies, those conducted in settings with a mean temperature above 20 °C gave a pooled relative risk of 1.024 (0.972–1.078), against 1.325 (1.125–1.561) in settings at or below 20 °C. That ordering is what a baseline-dependent association would produce, but it rests on four and two studies respectively, with substantial residual heterogeneity, and the

corresponding subgroups for road-traffic accidents do not show the same ordering — so it is suggestive rather than confirmatory. This hypothesis could be tested across populations spanning different baseline climates and thermal ranges.

Enclosed-vehicle occupants. Hsu *et al.* report an association among motor-vehicle occupants (1.14 at P95); we observed none. This is a difference in point estimates rather than a formally tested discrepancy (Section 3.7). This bears on mechanism, because an association that reaches occupants of air-conditioned vehicles is difficult to attribute to direct thermal exposure of the road user and is more consistent with the mechanisms acting on all road users discussed in Section 4.2 — degraded driving performance, traffic volume, pre-hospital care under strain. Our precision in this group is substantially lower (26,033 deaths against 126,668 exposed), so the difference may reflect power rather than a genuine contrast.

We emphasise that our data **do not support** the protective-enclosure hypothesis. Although the linear term differs between exposed and enclosed users (1.0181 vs 1.0028, $p = 0.0002$), estimating the full curve by group shows the two are not distinguishable in any heat band ($p = 0.21$ – 0.55); the only clear divergence is at the cold end. We report this comparison as exploratory.

Age. Latin America and China report risk highest in the young; we observed a U-shape with the maximum in those aged 65+ (1.0193) and the minimum in the middle-aged (1.0069). Because the pattern is U-shaped rather than inverted, this is not a direct contradiction, but it is unexplained; candidate explanations include mode composition by age, occupational exposure, and Thailand's rapid population ageing across the study period.

4.4 Implications for heat–health warning systems

Global burden analyses quantify how much road-injury burden is attributable to non-optimum temperature (Cui *et al.* 2023), but not where across the temperature range it accrues — and it is the latter that determines whether a threshold-based instrument is well matched to the problem. Heat–health warning systems are built on thresholds — a temperature or percentile above which alerts fire. Only 14.8% of the estimated temperature-associated excess occurred on days above the 95th percentile, and 8.8% when the estimand is anchored at the minimum-risk band. This suggests that interventions restricted to extreme-heat days would target temperature conditions accounting for only a small fraction of the estimated temperature-associated excess mortality. This is an argument about targeting, not about importance. The association with temperature is present, precisely estimated and, in aggregate, substantial; what the distribution shows is that it accrues mainly on days that are unremarkable enough to fall below any extreme-heat threshold. Read the other way round, the same result says that a large share of the temperature-associated burden sits on days that are frequent, predictable and already part of the ordinary operating conditions of the road system — which is an argument for sustained warm-season road-safety measures rather than for fewer measures. We are not estimating the effectiveness of any intervention. A warning system could alter behaviour, exposure or risk on subsequent days, and our design speaks to the distribution of associated deaths across temperature bands, not to what any programme would avert. What the distribution does suggest is that instruments calibrated to the warm season as a whole merit consideration alongside threshold-triggered alerts. The Songkran result (RR 1.311) is instructive by contrast: a date-bounded window of known elevated risk of that magnitude is well matched to a targeted campaign, and Thailand already runs one.

4.5 Limitations

- **No traffic-volume denominator, which conditions the principal finding.** The design estimates risk per day, not per vehicle-kilometre. Because the stratum absorbs province, year, month and day-of-week, only *daily* traffic volume would help, and no daily provincial series is published for Thailand. The shape of the association is also at risk: if travel declines on the hottest days, risk per trip could continue to rise where risk per day does not, and the observed plateau would reflect the denominator. This is also the quantity required to test the behavioural-adaptation hypothesis advanced in Section 4.2. We therefore state the finding as applying to mortality **per day**. Daily provincial counts of non-fatal injuries would resolve this, by allowing deaths/(deaths+injuries) to be modelled, in which traffic volume cancels. We note that Hsu *et al.* face the same limitation and cite evidence that adjustment for temporal trends and day-of-week yields results consistent with analyses that do include traffic-volume data; that argument bears on the *level* of the association rather than on its *shape*, which is what concerns us here.
- **Alcohol is unmeasured** and is plausibly on the causal pathway between heat and crashes.
- **Vehicle type is unspecified for 46%** of records, so road-user analyses rest on the classified subset.
- **Helmet and seatbelt fields are effectively empty** — absent in 13 of 16 years and 4–9% complete in the other three.
- **The geocoded subsample is not representative:** crash coordinates are absent after 2023 and differentially present by road-user type.
- **The crash-date subset is not representative** either: it is 53% motorcycle against 41% in the full file.

- **Exposure is station-based**, from an unevenly distributed network, and 13 provinces use a proxy station.
- **The residual wet-season/dry-season difference is unexplained** after adjustment for scale, rain and humidity.
- **The excess-mortality estimand is reference-dependent** (Section 3.4); magnitudes are not comparable to published attributable fractions without recomputation.

5. Conclusion

Warm days carry a higher risk of road-traffic death in Thailand. Relative to days of median temperature, mortality was about 3% higher on days in the P60–75 band and about 4–5% higher from P75 upward, with no evidence of further increase beyond that point. Because moderately warm days are far more numerous than extreme ones, they account for most of the temperature-associated deaths: approximately 72% of the estimated excess arose between P60 and P90, against 14.8% above P95. This pattern held under fine spatial exposure assignment, crash-date exposure assignment, exclusion of the Songkran holiday, consecutive-day heatwave definitions and humid-heat metrics.

The practical implication is that warm weather deserves sustained road-safety attention throughout the warm season — the period in which most of this burden arises — rather than attention concentrated on the rare days that cross extreme-heat alert thresholds, which carry a small share of it. That the association does not intensify further at the top of the temperature range is a finding about where to act, not a reason to act less.

Tables

Table 1. Binary extreme-heat-day definitions, on the same 283,847 deaths as Table 2.

Percentiles are province-specific; 5.2% of province-days reach P95 and 1.1% reach P99.

Definition	RR (95% CI), rain-adjusted	p	RR (95% CI), unadjusted	p
Tmax ≥ province P95, lag 0	1.015 (0.992–1.039)	0.210	1.022 (0.999–1.046)	0.064
Tmax ≥ province P99, lag 0	1.006 (0.953–1.063)	0.826	1.013 (0.959–1.070)	0.645
mean of lag 0–1 ≥ P95	1.012 (0.987–1.038)	0.345	1.018 (0.993–1.044)	0.152
mean of lag 0–3 ≥ P95	1.008 (0.983–1.034)	0.538	1.013 (0.987–1.039)	0.338

The rain-adjusted column is the one comparable to Table 2 and to the headline estimates.

Table 2. Exposure–response by province-specific percentile band of daily maximum temperature. Reference P40–60; adjusted for precipitation, Songkran and New Year; cluster-robust on province. n = 283,847 deaths.

Band	Mean Tmax (°C)	Deaths	RR (95% CI)
<P5	27.0	14,506	0.950 (0.924–0.976)
P5–25	30.5	56,619	0.968 (0.952–0.985)
P25–40	32.2	41,861	0.987 (0.969–1.006)
P40–60 (reference)	33.2	56,040	1.000
P60–75	34.2	42,857	1.033 (1.017–1.049)
P75–90	35.5	43,186	1.045 (1.023–1.068)
P90–95	36.9	14,362	1.044 (1.015–1.073)
P95–99	38.1	11,412	1.050 (1.018–1.083)
≥P99	39.8	3,004	1.041 (0.979–1.108)

Continuous: RR 1.0127 (1.0103–1.0152) per 1 °C increase in Tmax, centred at the province-specific median.

Table 3. Cell-level versus province-level exposure, fitted on the identical 107,313 geocoded deaths, 2012–2023. Correlation between the two exposures 0.752; mean absolute difference 2.95 °C.

Band	Cell-level (0.1°)	Province-level, same deaths
<P5	0.945 (0.907–0.983)	0.962 (0.926–1.000)
P5–25	0.966 (0.942–0.991)	0.965 (0.941–0.989)
P25–40	1.016 (0.991–1.041)	1.012 (0.987–1.037)
P40–60 (reference)	1.000	1.000
P60–75	1.033 (1.006–1.060)	1.061 (1.035–1.088)
P75–90	1.062 (1.034–1.090)	1.056 (1.028–1.085)
P90–95	1.084 (1.041–1.128)	1.074 (1.032–1.119)
P95–99	1.082 (1.033–1.134)	1.086 (1.039–1.136)
≥P99	1.011 (0.929–1.100)	1.082 (0.992–1.181)

Table 4. Excess deaths associated with temperatures above the P40–60 reference band, by band, and sensitivity of the estimand.

(a) Band decomposition

Band	RR	Deaths in band	Excess deaths	Share of excess
P60–75	1.033	42,857	1,371	30.4%
P75–90	1.045	43,186	1,874	41.6%
P90–95	1.044	14,362	599	13.3%
P95–99	1.050	11,412	546	12.1%
≥P99	1.041	3,004	119	2.6%
Total			4,509	100%
<i>of which ≥P95</i>			<i>665</i>	<i>*14.8%</i>

(b) Estimand sensitivity

Estimand	Excess deaths	95% CI	% of all deaths	Share ≥P95
vs P40–60, one-sided (reported)	4,509	2,581–6,442	1.59%	14.8%
vs P40–60, net of cooler-day deficit	1,325	–1,848 to 4,436	0.47%	—
vs minimum-risk band <P5, one-sided	15,454	9,177–21,918	5.44%	8.8%

567

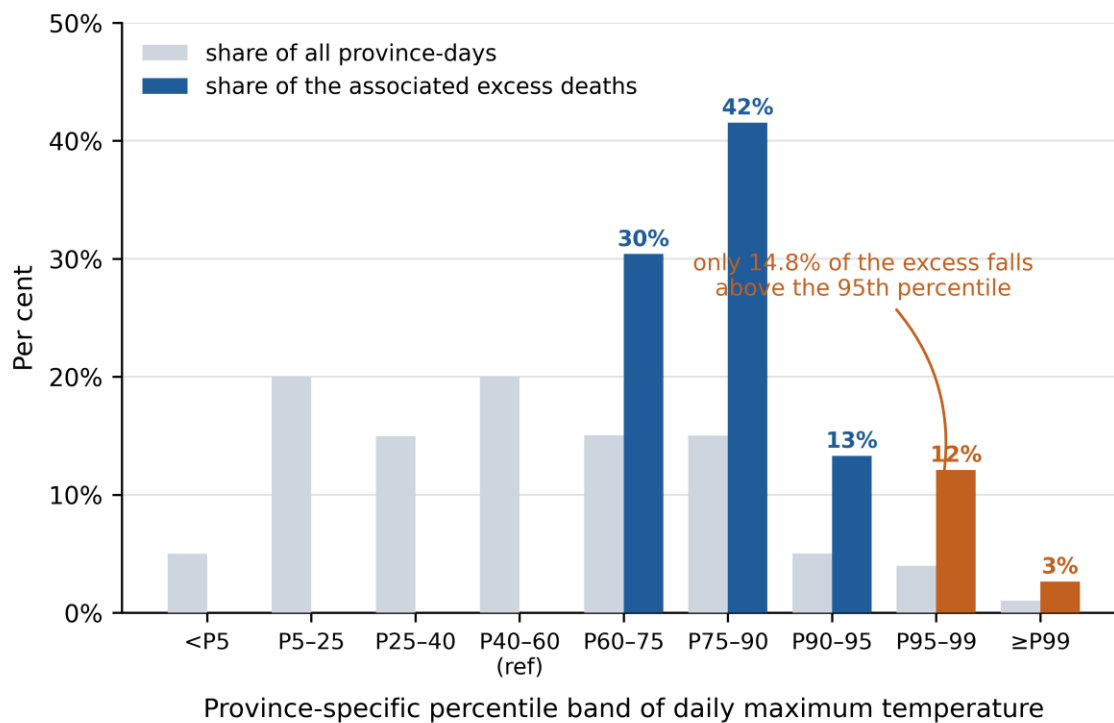
568 **Table 5.** Exposure assigned by date of death versus date of crash, fitted on the same 94,437
 569 individuals, 2011–2021.

Band	By death date	By crash date
<P5	0.950 (0.908–0.995)	0.935 (0.886–0.986)
P5–25	0.962 (0.940–0.985)	0.960 (0.934–0.988)
P25–40	1.003 (0.975–1.032)	0.996 (0.968–1.024)
P40–60 (reference)	1.000	1.000
P60–75	1.047 (1.020–1.076)	1.027 (0.996–1.060)
P75–90	1.070 (1.036–1.106)	1.048 (1.014–1.084)
P90–95	1.051 (1.001–1.103)	1.040 (0.990–1.093)
P95–99	1.071 (1.011–1.136)	1.013 (0.963–1.066)
≥P99	1.128 (1.036–1.229)	1.069 (0.982–1.163)

570

571 **Figures**

572 **Figure 1.** Distribution of the associated excess deaths across temperature bands, compared with
 573 the share of all province-days falling in each band. Bands above the 95th percentile are
 574 highlighted.



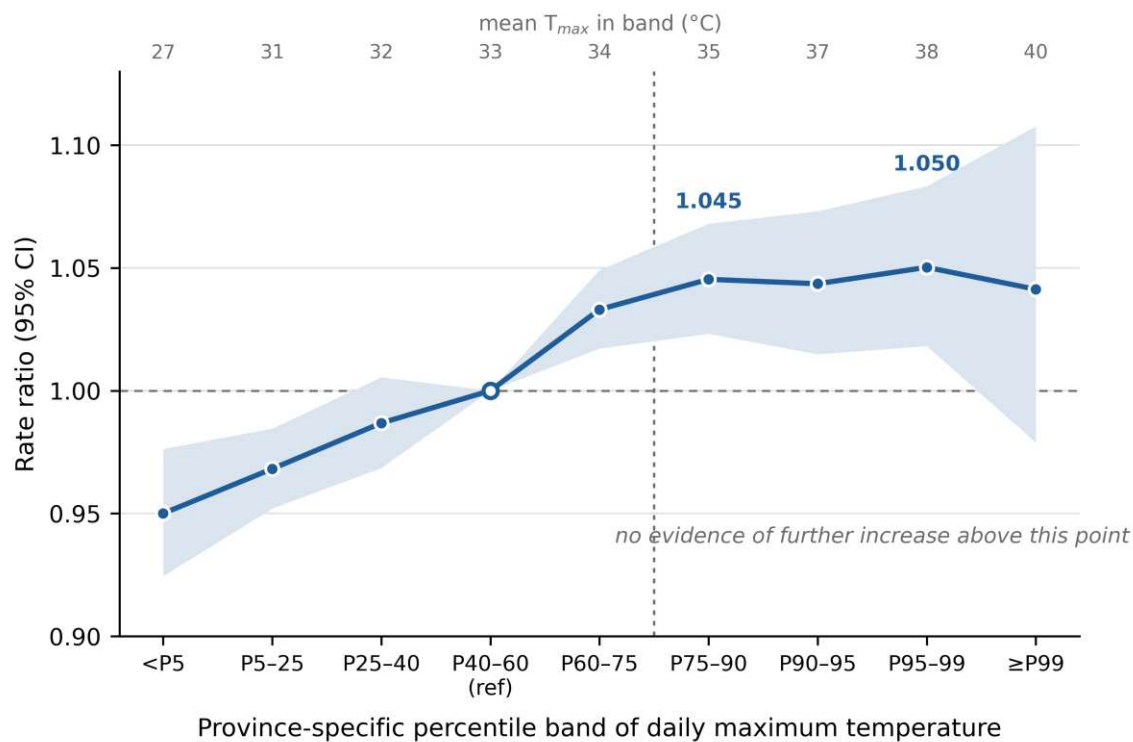
575 Province-specific percentile band of daily maximum temperature

576 **Figure 2.** Exposure–response curve for road-traffic mortality by province-specific percentile

577 band of daily maximum temperature, with 95% confidence intervals. Reference band P40–60.

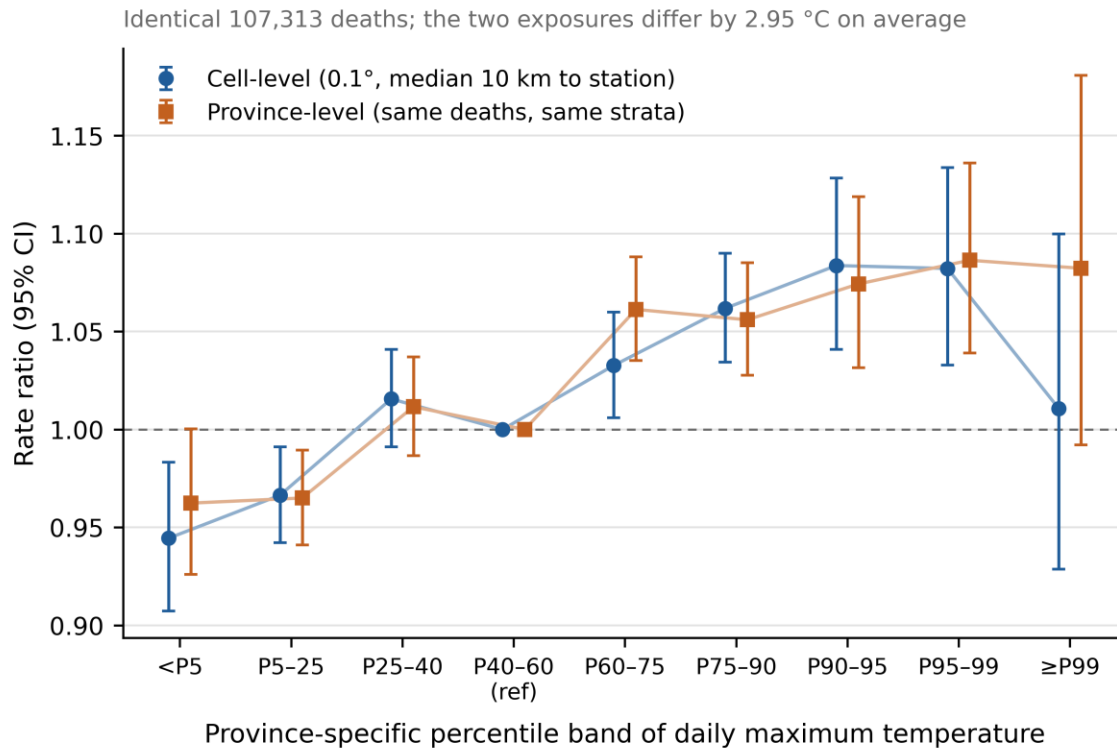
578 The dashed vertical line marks the point above which there was no evidence of further increase

579 in risk; it was identified from the estimates and was not specified in advance.



580

581 **Figure 3.** Exposure–response curves estimated at cell level (0.1°) and at province level on the
 582 identical 107,313 geocoded deaths, with 95% confidence intervals.



Supplementary Material

S1. Humid heat — metrics, nested interaction tests, seasonal standardisation. **S2.** Heatwave grid — 15 definitions, total and added effects, duration–response. **S3.** Crash-to-death interval — descriptives, logistic, spline, Cox, subgroups. **S4.** Minimum-risk-referenced estimates by road-user type. **S5.** Sensitivity analyses — proxy stations, pre/post-COVID, Tmean, season, and exclusion of the Songkran and New Year windows.

References

- Alduchov OA, Eskridge RE. Improved Magnus form approximation of saturation vapor pressure. *J Appl Meteorol* 1996;35:601–9.
- Aung HW, Kliengchuay W, Niampradit S, Aendo P, Aye TS, Intrakun S, Arthan D, Koompaong K, Lin T-H, Vardoulakis S, Lung S-CC, Tantrakarnapa K. Heat-related health impacts in ASEAN countries: a scoping review. *Environ Sustain Indic* 2026;30:101272. doi:10.1016/j.indic.2026.101272.
- Chua R, Ng YY, Ho AFW, Aik J. Association between climate variability and injury-causing road traffic accidents in Singapore — a time-stratified case-crossover study. *Urban Clim* 2025;59:102257. doi:10.1016/j.uclim.2024.102257.
- Cui Y, Yang W, Shuai J, Ma Y, Yan Y. High, low, and non-optimum temperatures exposure on road injuries in a changing climate: a secondary analysis based on the Global Burden of Disease Study 2019. *Environ Sci Pollut Res Int* 2023;30(4):11012–24. doi:10.1007/s11356-022-22903-2.
- Gasparrini A, Armstrong B. The impact of heat waves on mortality. *Epidemiology* 2011;22(1):68–73.
- He C, Yin P, Chen R, Gao Y, Liu W, Schneider A, Bell ML, Kan H, Zhou M. Cause-specific accidental deaths and burdens related to ambient heat in a warming climate: a nationwide study of China. *Environ Int* 2023;180:108231. doi:10.1016/j.envint.2023.108231.
- Hsu CK, Quistberg DA, Sánchez BN, Kephart JL, Bilal U, Gouveia N, Pérez Ferrer C, Caiaffa WT, de Lima Friche AA, Yannone I, Rodríguez DA. Individual and city-level variations in heat-related road traffic deaths in Latin America. *Nat Cities* 2025;2(9):897–906. doi:10.1038/s44284-025-00279-x. *Author Correction: Nat Cities* 2025;2(11):1107. doi:10.1038/s44284-025-00339-2.

613 Hu J, Huang S, Zhuo Y, Zhang J, Gong W, He G, Zhou M, Zeng F, Meng R, Liu T, Zhou C,
 614 Xiao Y, Yu M, Huang B, Bai G, Guo H, Ma W. The mechanism-specific injury mortality burden
 615 associated with heatwave in China in a warming world. *Environ Int* 2025;195:109241.
 616 doi:10.1016/j.envint.2024.109241.

617 Le VTH, Berman JD, Wattenberg EV, Ngo TV, Tran QA, Alexander BH. Temperature-related
 618 emergency injury visits in Hanoi, Vietnam. *Inj Prev* 2024;30(1):33–8. doi:10.1136/ip-2023-
 619 044946.

620 Liang M, Min M, Guo X, Song Q, Wang H, Li N, Su W, Liang Q, Ding X, Ye P, Duan L, Sun
 621 Y. The relationship between ambient temperatures and road traffic injuries: a systematic review
 622 and meta-analysis. *Environ Sci Pollut Res* 2022;29(33):50647–60. doi:10.1007/s11356-022-
 623 19437-y.

624 Pan R, Honda Y, Minakuchi E, Kim SE, Hashizume M, Kim Y. Ambient temperature and
 625 external causes of death in Japan, 1979–2015. *Environ Health Perspect* 2022;130(4):047004.
 626 doi:10.1289/EHP9943.

627 Vieira FL. Temperature exposure and analysis code for a nationwide study of road-traffic
 628 mortality in Thailand, 2011–2025 [dataset and code]. Zenodo; 2026.
 629 doi:10.5281/zenodo.22929209. <https://zenodo.org/records/22929210>

630 Zhou L, Liu C, He C, Chen R, Kan H. Heat-related risk and burden of hospitalizations for cause-
 631 specific injuries and the contribution of human-induced climate change. *Environ Health Perspect*
 632 2024;132(5):057005. doi:10.1289/EHP14057.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SupplementaryMaterialS1S5.docx](#)