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# Exposure-Adjusted Bicycle Crash Risk Estimation and Safer Routing in Berlin

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## Abstract

We investigate bicycle crash risk on Berlin's urban street network, addressing a key limitation of many safety analyses: raw crash counts conflate danger with demand and fail to distinguish intrinsically risky locations from high-use roads. We combine police-reported crashes with a city-wide dataset of measured bicycle volumes to compute exposure-adjusted risk at the street-segment and junction levels. Aggregating risk to arbitrary routes enables comparisons that trade off safety against convenience. The result is a reproducible framework for exposure-controlled bicycle safety analysis and routing.

## 1. Introduction

Cycling safety analyses often rely on raw crash counts, which conflate danger with demand: streets that attract many cyclists tend to accumulate more incidents even when per-rider risk is low (Lücken, 2018). This obscures intrinsically risky locations and limits both targeted interventions and everyday route choice, especially in dense urban networks such as Berlin (Uijtdewilligen et al., 2024). We address this by estimating exposure-adjusted crash risk on the street network via a relative-risk formulation that separates cyclist demand from intrinsic danger and remains stable under sparse or unevenly distributed observations (Section 3). Using police-recorded crashes from the German Unfallatlas (Berlin subset) (German Federal Statistical Office, 2025) together with a city-wide dataset of measured bicycle volumes at the street-segment level (Kaiser, 2025), we compute exposure-adjusted relative risk for individual street segments and, motivated by the concentration of crashes at intersections, derive junction-level risk by aggregating volumes from adjoining segments. The resulting risk estimates are transformed into expected crash costs and propagated to route-level scores, enabling the evaluation of arbitrary

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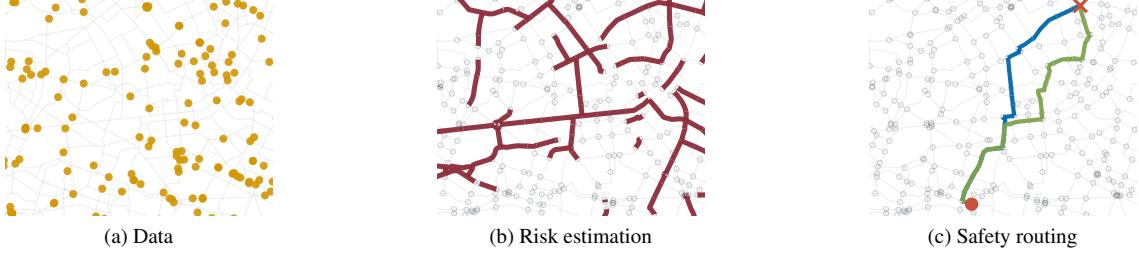
routes and comparisons between alternatives that reduce estimated risk while maintaining comparable convenience in terms of distance (Section 5), see Figure 1.

Taken together, this yields a reproducible pipeline for estimating exposure-adjusted crash risk at street and junction levels from measured cyclist volumes, and a route-scoring approach that integrates network-level risk into safety-aware routing under a bounded detour constraint.

## 2. Data

We combine police-recorded bicycle crashes with measured cyclist exposure for the city of Berlin. Crash data are drawn from the Berlin subset of the German *Unfallatlas* (German Federal Statistical Office, 2025) and filtered for bicycle-related incidents. Exposure comes from a city-wide dataset of measured bicycle volumes aggregated at the street-segment level (Kaiser et al., 2025b). The street network is represented as polyline segments with associated monthly cyclist counts. The resulting dataset spans 2019–2023 and covers 4,335 street segments and 2,862 junctions, with 15,396 recorded bicycle crashes. At monthly resolution the data are sparse: in a typical month fewer than 5% of segments and about 3% of junctions record at least one crash, and some periods include segments with zero measured exposure.

To enable network-scale analysis, all layers are harmonized to a common street-network topology and a projected coordinate reference system. Crash locations are matched to segments using nearest-segment assignment. To capture the concentration of crashes at intersections, we identify junctions as nodes where at least three segments meet; crashes within a fixed radius are assigned to the nearest junction, and junction exposure is computed from the exposures of incident segments. Matched crashes and exposures are aggregated to monthly resolution, and segments and months with zero exposure are dropped. To obtain stable risk estimates under sparse observations, monthly aggregates are pooled to yearly totals and an Empirical Bayes approach is applied as described in Section 3. The resulting yearly segment- and junction-level risk estimates serve as inputs to all routing analyses.



**Figure 1. Safety-aware routing pipeline for the Berlin cycling network.** Panels (a–c) show an example year (2021) and are zoomed in for readability; see Section 3 for formal definitions and notation. (a): Police-recorded bicycle crashes (points) and street segments with measured cyclist exposure (lines, used as the base network in all panels). (b): Yearly segment-level relative crash risk; high-risk segments in red correspond to the top 90th percentile of  $r_{s,y}$  in the displayed year. Circles mark junctions (degree  $\geq 3$ ), for which we also estimate junction-level relative risk from exposure aggregated over incident segments. (c): Shortest path (blue) versus a safer alternative (green) selected to reduce cumulative relative route risk under a distance-detour constraint. Filled circle and cross denote origin and destination, respectively; circles show junctions for reference.

### 3. Methods

**Empirical Bayes relative risk.** For each street segment  $s$  and month  $t$ , let  $A_{s,t}$  denote the number of police-recorded bicycle crashes and  $E_{s,t}$  the measured cyclist exposure. We assume that, within a given month, crash incidence is proportional to exposure under a “no special risk” baseline, yielding the expected number of crashes

$$\hat{A}_{s,t} = A_t \frac{E_{s,t}}{E_t}, \quad A_t = \sum_s A_{s,t}, \quad E_t = \sum_s E_{s,t}.$$

Although crashes and exposure are aggregated at monthly resolution in preprocessing, sparse observations motivate estimating relative risk at yearly resolution. For each year  $y$  comprising months  $\mathcal{T}(y)$ , we pool monthly aggregates to yearly totals

$$A_{s,y} = \sum_{t \in \mathcal{T}(y)} A_{s,t}, \quad E_{s,y} = \sum_{t \in \mathcal{T}(y)} E_{s,t},$$

and define  $A_y = \sum_s A_{s,y}$  and  $E_y = \sum_s E_{s,y}$ . The corresponding baseline expectation is

$$\hat{A}_{s,y} = A_y \frac{E_{s,y}}{E_y}.$$

To obtain stable estimates under sparse observations, we introduce a latent relative-risk multiplier  $\theta_{s,y}$  and model

$$A_{s,y} \mid \theta_{s,y} \sim \text{Poisson}(\hat{A}_{s,y} \theta_{s,y}), \\ \theta_{s,y} \sim \text{Gamma}(\alpha, \alpha),$$

where the Gamma distribution is parameterized in shape-rate form, enforcing a unit prior mean  $\mathbb{E}[\theta_{s,y}] = 1$ . The hyperparameter  $\alpha$  is estimated via empirical Bayes by maximizing the marginal likelihood pooled across all segments

and years. By conjugacy, the posterior mean

$$r_{s,y} = \mathbb{E}[\theta_{s,y} \mid A_{s,y}, \hat{A}_{s,y}] = \frac{\hat{A}_{s,y} + \alpha}{\hat{A}_{s,y} + \alpha}$$

serves as our smoothed segment-level relative risk. This estimator shrinks extreme values toward 1, with stronger shrinkage for segments with low expected crash counts.

To capture the concentration of crashes near intersections, we also estimate junction-level relative risk. A junction is defined as any network node with degree  $\geq 3$ ; crashes within a fixed radius of its centroid are assigned to that junction. Because a traversal typically contributes exposure to two incident segments (entering and exiting), we approximate junction exposure by a half-sum of incident segment exposures,

$$E_{v,y} = \frac{1}{2} \sum_{s \in \mathcal{I}(v)} E_{s,y}, \quad (1)$$

which avoids double-counting. Aggregating exposure over incident links is common when turning movements are unavailable (Hakkert et al., 2002; Wang et al., 2020). The expected number of junction crashes is defined as  $\hat{A}_{v,y} = A_y E_{v,y} / E_y$ , and junction relative risk  $r_{v,y}$  is estimated using the same Empirical Bayes formulation and hyperparameters as for segments. All risks are estimated independently by year.

**Routing graph.** For each year  $y$ , we build an undirected graph  $G_y = (V_y, E_y)$  from the street network: nodes represent segment endpoints and edges represent street segments with length  $\ell_e$ . Each graph edge  $e$  corresponds to a street segment  $s$  and inherits its estimated yearly risk, denoted  $r_{e,y} = r_{s,y}$ . Junction identifiers and risks are mapped to nodes via spatial snapping in a projected coordinate system, yielding a year-specific, risk-annotated network.

**Safety-aware routing.** We compare shortest-distance routes with alternatives that reduce estimated crash risk under a bounded detour. For year  $y$ , the length of a route  $P$  is

$$L(P) = \sum_{e \in P} \ell_e.$$

To account for both segment- and junction-level exposure, the risk contribution of edge  $e = (u, v)$  is defined as

$$\rho_{e,y} = r_{e,y} + \eta \frac{r_{u,y} + r_{v,y}}{2},$$

where  $r_{u,y}$  and  $r_{v,y}$  are junction risks (set to zero for non-junction nodes) and  $\eta \geq 0$  weights the contribution of junction risk. We interpret these relative-risk weights as an *additive surrogate* for cumulative route risk, not as probabilities.

Given an origin–destination pair, the baseline route  $P_{\text{dist}}$  minimizes  $L(P)$ . The safety-aware route solves

$$\begin{aligned} P_{\text{safe}} &= \arg \min_P R(P) = \sum_{e \in P} \rho_{e,y} \\ \text{s.t. } L(P) &\leq (1 + \varepsilon) L(P_{\text{dist}}), \end{aligned} \quad (2)$$

where  $\varepsilon$  is the allowable relative detour. We approximate this constrained problem using a weighted-sum sweep: for  $\lambda \in \Lambda$ ,

$$P(\lambda) = \arg \min_P \sum_{e \in P} (\rho_{e,y} + \lambda \ell_e),$$

then select among feasible candidates the route with minimal  $R(P)$ , breaking ties by shorter  $L(P)$ . Shortest paths are computed using Dijkstra’s algorithm. Routing is performed independently by year.

**Evaluation metrics.** For each origin–destination pair, we report the relative length increase

$$\Delta_L = \frac{L(P_{\text{safe}}) - L(P_{\text{dist}})}{L(P_{\text{dist}})}$$

and the relative risk reduction

$$\Delta_R = \frac{R(P_{\text{dist}}) - R(P_{\text{safe}})}{R(P_{\text{dist}})}.$$

Pairs with  $R(P_{\text{dist}}) = 0$  are excluded from  $\Delta_R$  due to an undefined denominator. These metrics quantify how bounded detours trade distance for reductions in relative crash risk.

## 4. Related work.

Prior work has aimed to avoid conflating danger with demand by normalizing bicycle crashes by cyclist exposure (Lücke, 2018). City-scale studies demonstrate that

exposure-normalized risk yields more informative spatial patterns than raw crash counts, and that finer temporal resolution improves inference, though persistent under-reporting in police records remains a challenge (Uijtdewilligen et al., 2024). A central obstacle in this line of research is obtaining reliable exposure: earlier methods extrapolate city-wide volumes from sparse counters using learning-based models and multi-source features, while short-term measurement campaigns improve predictions at unseen locations (Kaiser et al., 2025a). More recent efforts leverage street-segment datasets of measured bicycle volumes, enabling downstream safety analyses without the need to model exposure (Kaiser et al., 2025b). At the network level, studies define risk as crashes per unit exposure on links and address practical challenges such as spatial snapping of crash events, assigning incidents to intersections, and integrating safety metrics into routing under convenience constraints (Wage et al., 2022). The role of intersection safety is emphasized across multiple studies, which document strong crash concentrations at junctions and highlight the importance of controlling for exposure when comparing infrastructure types or locations (Medeiros et al., 2021).

## 5. Results

### 6. Discussion and Conclusion

We provide implementation details, hyperparameters, and supplementary material, available at [https://github.com/ytobiaz/data\\_literacy](https://github.com/ytobiaz/data_literacy).

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