From Uncertain District-Level Crash Risk to Enforcement Capacity Planning: A Bayesian Hierarchical and CVaR-Based Multiobjective Framework

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Abstract

District-level road-safety decisions often rely on historical crash counts despite sparse severe events, endogenous enforcement activity, and constrained operational capacity. This study develops an uncertainty-aware predict-then-optimize framework for marginal traffic-enforcement expansion across 17 districts of Bursa, Türkiye, using a balanced 2020-2024 panel of 85 district-year observations. Property-damage-only and injury crashes are modeled with Bayesian hierarchical negative-binomial models, while fatal crashes use a hurdle-negative-binomial specification. A strict 2024 temporal holdout compares Bayesian models with Poisson, negative-binomial, XGBoost, and random-forest benchmarks. Posterior predictive draws are converted into severity-weighted district-risk scenarios and transferred to a three-objective integer program minimizing 95% conditional value-at-risk of unmet risk, response-weighted unmet risk, and a normalized expansion proxy. Mean combined risk is highest in İznik, İnegöl, and Osmangazi. The ideal-point compromise adds one team to Orhaneli and 11 personnel across four districts, reducing the two risk-oriented objectives by 9.80% and 16.06%. NSGA-II recovers all six retained AUGMECON2 reference points. The framework supports transparent risk-responsive capacity planning without interpreting observational enforcement associations as causal effects.

Keywords

Bayesian hierarchical count model, conditional value-at-risk, crash-risk prediction, enforcement capacity, multiobjective optimization.

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