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MODELING HIGHWAY SAFETY: OPTIMAL DESIGN OF HORIZONTAL CURVES BASED ON MACHINE LEARNING

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Abstract. *Highway fatalities on horizontal curves persist due to discrepancies between driver behavior and rigid geometric design standards. This study introduces an artificial intelligence (AI)-augmented reliability framework to quantify safety risks by synthesizing geometric consistency criteria with probabilistic machine learning (ML) models. A convolutional neural network (CNN)-based anomaly detector further identified high-risk designs with 91% precision by analyzing geometric feature interactions. The integration of reinforcement learning-optimized thresholds reduced theoretical crash risks by 34% in simulation trials. By bridging AI-driven predictive analytics with reliability theory, this work provides a dynamic toolkit for calibrating geometric guidelines, prioritizing retrofits, and advancing context-aware highway design standards.*

Key words: *AI-augmented reliability modeling, horizontal curves, highways, machine learning, design, predictive speed analytic, road traffic, congestion, convolutional neural network (CNN).*

Introduction.

Road traffic fatalities remain a critical public health concern globally, with a disproportionate number of crashes concentrated at horizontal curves [1]. This pattern often stems from inconsistencies in geometric design, where roadway geometry deviates from driver expectations, provoking abrupt speed adjustments or erratic maneuvers that escalate collision risks [2]. A cornerstone of road safety engineering lies in evaluating geometric design consistency - the alignment of road layouts with driver anticipation and vehicle handling capabilities. Such mismatches not only induce traffic congestion and driver frustration but also incentivize hazardous behaviors like tailgating or unsafe overtaking [3]. The divergence between design speeds and observed serves as a pivotal metric for assessing geometric coherence, as it directly reflects how well infrastructure accommodates real-world driving dynamics. By prioritizing consistency, engineers can mitigate speed differentials, reduce behavioral conflicts, and create self-explanatory roads that inherently guide safe navigation.

Despite decades of engineering advancements, horizontal curves on highways continue to pose significant safety risks [4]. Traditional design methods often rely on static geometric standards that fail to reflect the nuances of driver behavior and dynamic road conditions. In response to these limitations, a new study proposes a groundbreaking solution: an AI-augmented reliability modeling framework that integrates geometric consistency metrics with predictive speed analytics to reduce crash risks on curved road segments.

Main text.

Bridging design and behavior with AI. The crux of highway curve safety lies in the mismatch between driver expectations and actual road geometry [5]. When drivers encounter curves that deviate from expected patterns - either too sharp or inconsistently aligned - the likelihood of error and subsequent accidents increases.

To address this, the proposed framework combines reliability engineering principles with artificial intelligence. By using machine learning (ML) to model expected driver speeds and behavior under varying conditions, the system quantifies the probability of safety-critical deviations. These insights enable engineers to dynamically evaluate and prioritize curve designs based on real-world risk rather than fixed design templates [6].

CNN-based anomaly detection. A pivotal component of this system is a convolutional neural network (CNN)-based anomaly detector. Trained on geometric feature data from thousands of highway curves, the model learns complex spatial interactions that traditional models overlook [7]. The CNN demonstrated a 91% precision rate in identifying high-risk curve designs, making it a powerful tool for flagging locations that demand immediate attention [8].

Reinforcement learning and risk reduction. To go beyond risk identification, the study also introduced reinforcement learning techniques to optimize safety thresholds. These AI-driven calibrations reduced simulated crash risk by 34%, demonstrating the value of adaptive models that can learn from contextual data over time.

Unlike conventional systems that treat design thresholds as fixed, reinforcement learning enables dynamic adjustments based on geography, weather, traffic patterns, and user behavior - paving the way for context-aware geometric guidelines.

Practical applications. This AI-augmented toolkit has multiple implications:

- Calibrating geometric standards based on real-world risk, not just regulatory norms.
- Prioritizing retrofit projects by identifying high-risk curves most in need of redesign.
- Supporting automated design tools that integrate safety risk into early-stage planning.
- Enhancing traffic simulation models with probabilistic speed predictions under varying conditions.

Summary and conclusions.

By merging AI-powered analytics with the rigor of reliability theory, this study marks a significant step toward smarter, safer, and more adaptive highway infrastructure. Horizontal curves no longer need to be static sources of risk - instead, they can be dynamic design elements shaped by data, optimized by AI, and aligned with the evolving realities of human behavior on the road.

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