

Summary

As a crucial node for the inflow and outflow of multiple traffic flows, weaving sections are characterised by complex vehicle interactions and high conflict potential. They may represent bottlenecks where crash risk is particularly prominent. Frequent and complex lane-changing behaviour primarily causes a decline in both traffic efficiency and safety. Nevertheless, weaving sections remain an indispensable element of road design. They provide essential merging, diverging, and lane-changing opportunities between closely spaced ramps and the mainline, thereby maintaining network continuity and access, while concentrating weaving manoeuvres within a defined segment to reduce unregulated lane changes along the mainline. In many cases, their use is further dictated by limited right-of-way, cost constraints, and the need to connect conflicting traffic streams. Systematically analysing lane-changing mechanisms and accurately predicting collision risk holds great theoretical value and practical significance for improving expressway safety. This thesis focuses on lane-changing behaviour and collision risk in expressway weaving sections, following a complete research chain from characteristics analysis to decision mechanism explanation, risk factors identification, and active risk prediction.

A driving simulation scenario was built based on drone-collected field data to ensure high fidelity to real-world conditions. The response surface centre composite design method was used to design experiments with recruited drivers. Efficiency and lane-changing behaviour metrics were selected as key characteristics. The two-sample Kolmogorov-Smirnov test comprehensively compared distribution characteristics between simulator and field data. Results show consistency alongside systematic differences driven by interactions among data collection methods, lane-changing types, and demographic characteristics.

Three key decision-making metrics were selected: lane-changing start position, accepted target lane lead gap, and accepted target lane lag gap. Hierarchical

Bayesian and double-hurdle extension models were established to capture unobserved heterogeneity by data type, lane-changing type, and lane-changing event level through random effects. Left lane changes require longer preparation distances than right ones. Surrounding vehicle size and type are key factors affecting position choice, while speed compression from following vehicles prompts more backward positioning. The double-hurdle model confirms two-stage decision independence, where binary gap acceptance and continuous gap size decisions are dominated by different factors, including relative motion characteristics and vehicle status.

The Lane Change Risk Assessment Index (LCRAI) was constructed by combining risk exposure and severity indexes through fault tree analysis. Enhanced K-means clustering divided events into extremely low, low, moderate, and high-risk levels. A random-parameter ordered Probit model considering heterogeneity of mean and variance was established after screening key variables. Results indicate that vehicle physical attributes, motion state, relative motion, decision results, and situational elements together constitute the key variable set. Dynamic motion and relative motion characteristics demonstrate higher influence intensity than static attributes.

Static and dynamic candidate feature sets were constructed using a feature engineering method combining spatial clustering enhancement and boundary cleaning sampling. An information fusion mechanism based on spatio-temporal representation decoupling was proposed with grade consistency maximisation as the objective function. A heterogeneous fusion framework combining XGBoost and GRU-KAN achieved optimal prediction performance at a 1-second warning window. SHAP interpretability analysis confirmed that kinematic characteristics dominate risk assessment and that lane-changing decisions causally relate to collision risk. Vehicle size and lane-changing motivation are important prerequisites. Three representative micro-dynamic evolution paths including sudden acceleration and deceleration alternation, forced lane changes, and consecutive lane changes were successfully extracted to concretise high-risk temporal evolution.

Main innovations of this thesis include four aspects. First, microscopic lane-changing characteristics were systematically validated to reveal systematic differences and complementary relationships between simulation and field data. Second, a hierarchical Bayesian lognormal double-hurdle modelling framework was proposed to analyse two-stage decision mechanisms and expand theoretical categories. Third, a comprehensive quantitative LCRAI was constructed based on risk exposure and severity indexes, and a heterogeneity-aware cause analysis model

identified key risk factors and their influence mechanisms. Fourth, a heterogeneous fusion risk prediction framework with grade consistency optimisation was developed to reveal characteristic mechanisms and temporal evolution patterns of high risk, providing technical support for real-time warning and differentiated intervention in Advanced Driver Assistance Systems (ADAS).

Type of Dissertation and Related Publications

This dissertation is presented in the form of a monograph, a single, comprehensive manuscript presenting a unified piece of original research. However, portions of the research contained herein have been disseminated through peer-reviewed publications. The following papers have been produced during this doctoral study, and the corresponding sections of this manuscript are indicated for each:

- (1) Gao, D., Lee, J. J., & **Mao, S.** (2026). Systematic review of weaving area safety: Assessment, behavior, and countermeasures. *Accident Analysis & Prevention*, 230, 108470. <https://doi.org/10.1016/j.aap.2026.108470>. (Published)

This work corresponds to Chapter 1 of this dissertation.

- (2) **Mao, S.**, Lee, J. J., Karimi, A., Lioi, A., & Bassani, M. (2025). Validation of lane-changing behaviour in a weaving section using a driving simulator experiment. *Transportation Research Part F: Traffic Psychology and Behaviour*, 115, 103364. <https://doi.org/10.1016/j.trf.2025.103364>. (Published)

This work corresponds to Chapters 2 and 3 of this dissertation.

These publications have been integrated into the present monograph to form a coherent and continuous dissertation. The list above is provided for transparency and does not change the monograph nature of this dissertation.