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Analysis of Individual Lane-Change Behavior and Interaction among Vehicles Caused by Lane Closure on Highway Using 10-Networked Driving Simulators

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Background and Objectives

Advanced Driver Assistance Systems (ADAS) and Cooperative Intelligent Transport Systems (C-ITS) require a deep understanding of human factors and complex driver interactions. While previous networked driving simulator (DS) studies have successfully developed system integration technologies, they lacked a clear experimental methodology for extracting and quantitatively evaluating natural multi-agent interactions. Furthermore, conventional discrete choice models formulating driving behavior often suffer from low spatial resolution, necessitating complex nested structures like the Cross-Nested Logit (CNL) model to absorb unobserved correlations.

The primary objective of this study is to establish a comprehensive experimental methodology using a unique 10-networked DS system. By observing natural driver interactions during a highway lane-closure scenario, we propose a high-resolution, non-linear Multinomial Logit (MNL) model without complex nested structures to precisely extract and analyze micro-level driving characteristics.

Methodology

To capture universal and complex driving behaviors, we defined a high-resolution grid system consisting of 105 grids (21 columns times 5 rows) representing the agent's spatial directional choices. At each 0.1 s time step, the agent evaluates risk and utility across all grids. The utility functions incorporate various risk perception factors: relative distance and speed to the preceding vehicle, approaching road boundaries, side boundaries and obstacles, predicted future trajectories of surrounding vehicles, destination directivity, free-flow acceleration/deceleration, and lane-keeping preferences. The total utility determines the probability of grid selection using the non-linear MNL model. Based on the selected spatial target, the vehicle's yaw rate is controlled, and longitudinal acceleration is managed by the Intelligent Driver Model (IDM). To gather empirical data, a human-in-the-loop experiment was conducted using the 10-networked DS system with ten participants. The scenario simulated a highway merge caused by a lane closure, intentionally inducing natural negotiations between three vehicles in the closing lane and seven in the main lane. We continuously logged vehicle states and driver control inputs at 50 Hz. Finally, we employed a three-step heuristic process using Biogeme to estimate the model's parameters (sensitivities β and non-linear shape parameters λ) effectively mitigating multi-collinearity and calculation explosion.

Numerical Example

Parameter estimation was conducted focusing on a specific vehicle ("Agent 6") executing a lane change from the closing lane. The estimated parameters demonstrated high statistical significance (p < 0.05). The quantitative behavioral profile revealed that Agent 6 strongly avoided road boundaries and side obstacles. During the lane closure taper, the agent experienced a "sandwich" effect—squeezed by the approaching left road boundary ($\beta_{keepside\_L} = -5.37$) and right-side vehicles ($\beta_{side\_R} = 5.59$). The decisive factor enabling the lane change was a remarkably strong preference for the predicted future space of other vehicles in the target lane ($\beta_{future} = -10.4$), effectively overcoming the spatial constraints. To validate these findings, a trajectory reproduction simulation was performed under identical traffic conditions, comparing the actual driving data ("Real") with the simulated agent ("Ghost"). The Ghost agent successfully replicated the trajectory, including the transition to and maintenance of the target lane, effectively avoiding the closed lane. Although the Ghost initiated the lane change slightly earlier than the Real driver, the overall spatial choices strongly validated the rationality of the estimated parameters and the proposed utility functions.

Conclusion

This study established a robust analytical methodology integrating the 10-networked DS experiment, non-linear MNL parameter estimation, and Ghost trajectory validation. This deductive verification cycle proved highly effective not only for extracting micro-level decision-making mechanisms but also for quantitatively validating the mathematical models in a near white-box manner. Future work will address the independent calibration of the IDM parameters to improve longitudinal dynamic accuracy and expand this analytical framework to all experimental agents and various traffic scenarios, further solidifying this multi-agent driving simulation methodology.