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Effectiveness evaluation of trajectory planning at highway merging sections using quantum-inspired optimization

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This paper investigates an autonomous driving trajectory planning method for highway merging scenarios by formulating the problem as a Combinatorial Optimization Problem (COP) and solving it using a quantum-inspired optimization. Highway merging is one of the most challenging driving situations due to limited merging lane length, incomplete visibility of mainline traffic from the ramp, and the need to coordinate with multiple other vehicles under time constraints. While recent advances in sensors and machine learning have enabled complex maneuvers on general roads, trajectory planning remains difficult when other vehicles are outside the sensing range.

Assuming a future environment where V2X infrastructure is widely deployed, the proposed approach leverages upstream information on mainline vehicles provided via V2X. The objective is to generate, during ramp-way driving, a "preparatory" trajectory that brings the ego vehicle into a state where safe and comfortable merging can be easily executed. To handle uncertainty in other vehicles' behavior, the method explicitly predicts multiple possible trajectories for other vehicles and optimizes the ego trajectory against these alternatives.

Both ego-vehicle trajectory planning and multi-hypothesis prediction of other vehicles are discretized and formulated as a large-scale COP, where each candidate trajectory is assigned to a binary variable. A cost function evaluates merging desirability based on factors such as available free space, relative velocity, upstream merging position, consistency with observed time headway (THW) patterns, and smoothness of acceleration. Constraints enforce the selection of a single ego trajectory and a fixed number of trajectory hypotheses for each other vehicle. Due to the combinatorial explosion of possible combinations, a quantum-inspired machine (Ising machine) is employed to perform high-speed, wide-area search.

The proposed method is evaluated through simulation-based use-case verification using real highway geometry and real traffic data. Specifically, vehicle trajectory data from the Hanshin Expressway Zen Traffic Data (ZTD) database are used to construct six realistic merging scenarios. Simulation results are compared directly with actual human driving behavior in identical scenes. The results show that the proposed approach can guide the ego vehicle to merge into free spaces located 20–70 meters further upstream than those observed in real traffic, indicating smoother and more desirable merging behavior in many cases.

Computational performance is also evaluated. In a representative case involving over 1,200 quantum bits, the quantum-inspired optimization converges within approximately 0.8 seconds, demonstrating feasibility for near–real-time application. The study further discusses limitations related to long-horizon prediction accuracy and identifies future work, including expanding the range of applicable merging scenarios and generalizing the approach to other driving situations.

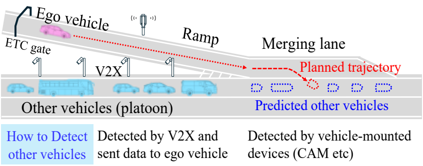


Fig.1 Highway merging with V2X

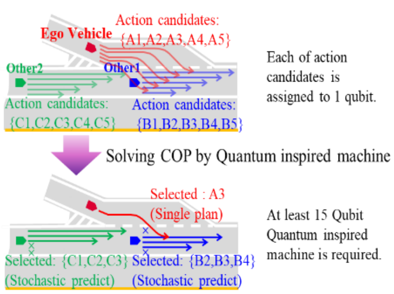


Fig.2 Example of COP in this study

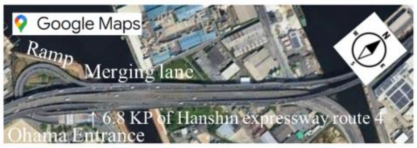
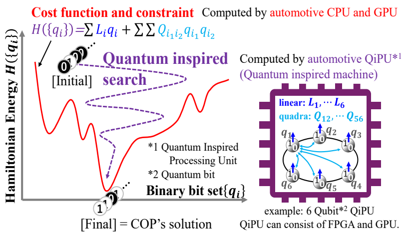


Fig.3 Real highway geometry of use-case verification



$H(\{q_i\})=\sum L_i q_i + \sum\sum Q_{i_1 i_2} q_{i_1} q_{i_2}$

Fig.4 High speed search using Quantum inspired optimization

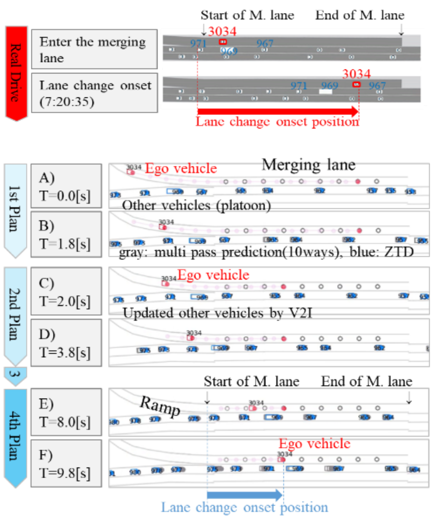


Fig.5 Compare Real and SIM result of use-case verification