OPTIMAL ECO-DRIVING CONTROL WITH HUMAN FEEDBACK FOR INTELLIGENT VEHICLES

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論文名　Title：　OPTIMAL ECO-DRIVING CONTROL WITH HUMAN FEEDBACK FOR INTELLIGENT VEHICLES
（インテリジェント車両のための人間フィードバックによる最適なエコ運転制御）

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論　文　内　容　の　要　旨

Thesis Summary

The development of the automotive industry brings benefits to modern transportation, but it has also led to significant challenges in terms of energy and environmental issues. Intelligent vehicles, driven by connected and automated technologies, have provided unprecedented opportunities for energy-efficient and decarbonized driving control. In this context, eco-driving control for connected and automated vehicles (CAVs) has been of high interests in academic and industrial research in recent years. The core idea of eco-driving is the real-time optimization of driving decisions and powertrain control leveraging ubiquitous sensing and prediction of future road traffic information from intelligent transportation systems (ITS). By considering the influence of road traffic conditions on vehicle energy economy, eco-driving aims to harmonize vehicle motion with surrounding road conditions, traffic status, and driving performance, which can greatly improve driving energy efficiency. However, there are still scientific challenges existing in facilitating the real implementation of eco-driving as follows: 1). From the perspective of optimization problem formulation, a critical challenge lies in the full integration of external traffic information into the optimal control of the powertrain and velocity, while effectively handling constraints from preceding vehicle, traffic signal lights, and even the microscopic traffic dynamics ahead. 2). From the perspective of optimal control problem solution, the introduction of rich traffic information with nonlinear dynamic characteristics of the vehicle powertrain system significantly increases the complexity of the optimal control problem, making it challenging to achieve real-time computation. 3). From the perspective of practical applications, eco-driving prioritizes the energy consumption minimization by adopting smoother acceleration or lower speeds, which might conflict with human driver's preferences on traveling demands. Hence, how to align the eco-driving control with human feedback to ensure user acceptance becomes another challenge that needs to be solved.

To address the aforementioned challenges, this thesis is oriented toward engineering practice while focusing on theoretical methodologies and conducting research on the topic of optimal eco-driving control with human feedback for intelligent vehicles through the following three aspects of investigation. Firstly, a real-time predictive cruise control (PCC) system is developed to enhance the eco-driving of electric vehicles in urban traffic environments. Considering the constraints from surrounding traffic participants and upcoming traffic signals, the system employs a bi-level architecture comprising dual linear model predictive controllers (MPC) with switching logic, which enables receding-horizon optimization of motor torque and braking force. This allows the host vehicle to safely follow the preceding vehicle and navigate through signalized intersection during green-light intervals. Secondly, a novel lane-changing motion planning strategy for personalized energy-efficient autonomous driving is proposed and solved in real-time through the parallelizable interior-point method (IPM). To generate a safe and feasible lane-changing trajectory, two safe driving envelopes are considered for vehicle dynamics limitations and safe lane-changing areas. Additionally, a driving style identification model is developed based on multi-class Gaussian process classification. Verified through a Human-in-the-Loop (HiL) driving simulator, the approach demonstrates its ability to achieve energy-efficient lane changes while accommodating drivers' personalized driving preferences. Finally, a real-implementable human-inspired anticipative cruise

control strategy is proposed for CAVs to align with the human driver's reactive driving preferences while leveraging their anticipative capabilities to improve overall traffic efficiency in mixed traffic flow. The introduction of a recovery matrix enables learning from human demonstration. By leveraging a linear-quadratic optimal control with look-ahead functionality, this strategy achieves performance comparable to predictive optimization, but with significantly lower computational demands, operating at millisecond-level efficiency.

The proposed real-time PCC system was evaluated in realistic driving environments, demonstrating a reduction in energy consumption of up to 8.5% for the host vehicle with the proposed eco-driving PCC system in suburban areas, as compared to conventional human driver behavior. In urban settings, the system achieved energy savings of up to 15.6% due to the velocity trajectory optimization considering the signal phasing and timing (SPaT) information of the upcoming traffic signals. Furthermore, the linearized model predictive control allows the PCC system to perform real-time computations with 5.23 milliseconds for each sampling interval. In terms of the proposed lane-changing motion planning strategy, the experimental result reveals energy savings of 2.87-5.73% during lane change compared with human-driven maneuvers. Taking a typical automatic lane-change model as the benchmark, the proposed algorithm not only achieves energy-efficient lane changes but also effectively identifies and integrates personalized driving styles into the control strategy. Moreover, the latent nonlinear MPC achieves a computational time of 10 milliseconds by using the parallelizable solution method. As for the human-inspired anticipative cruise control strategy, HiL simulative results validate its real-time implementation potential in effectively learning human-like reactive driving control preferences and improving the overall traffic flow energy economy by 4.58%. Additionally, it enhances traffic throughput by mitigating latent traffic oscillations. The computational time, which includes solving the constrained quadratic optimization problem for real-time traffic anticipation and evaluating explicit control law, is approximately 26 milliseconds, making the proposed control strategy feasible for practical deployment.

In conclusion, eco-driving control with human feedback for intelligent vehicles represents a multidisciplinary engineering challenge. Leveraging the real-time optimization-based control and insights from human feedback, this thesis addresses key scientific and technical issues, including the efficient integration of connected traffic information into automotive control, the rapid solution of optimization problems, and the alignment of control objectives with human preferences. These contributions collectively advance the intelligent energy-saving capabilities of vehicles and decarbonization efforts within the automotive industry.