Uncertainty Propagation in Economic and Tracking MPC for Energy-Efficient Autonomous Train Control

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Abstract

Energy-efficient train control has received substantial attention in the railway literature, with trajectory optimization commonly used to generate energy-efficient reference trajectories under nominal conditions. However, in real operation these trajectories are affected by calibration errors, modeling simplifications, and disturbances, making closed-loop control essential. The interaction between trajectories, uncertainty, and control performance remains insufficiently understood.

This paper studies the impact of uncertainty on autonomous train operation by comparing Tracking MPC and Economic MPC. The analysis is conducted in simulation with controlled parameter uncertainty in the train dynamics. A global sensitivity analysis quantifies how uncertainty propagates through the control pipeline and affects key performance indicators, including energy efficiency, punctuality, and tracking accuracy.

Results show that performance is most sensitive to mass calibration errors, which dominate both energy and tracking degradation. Both controllers remain close to optimal performance under significant uncertainty, but clear trade-offs emerge: Tracking MPC achieves superior tracking accuracy, while Economic MPC yields lower energy consumption in isolated operation. Overall, the study provides quantitative insight into uncertainty propagation in energy-efficient train control and highlights trade-offs between tracking performance and energy optimality, offering guidance for controller selection and calibration prioritization in autonomous train systems.

Keywords

Autonomous train control; Energy efficiency; Optimal control; Uncertainty