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Concept of Energy-Saving Operation for Electric Vehicles Under Time and Speed Constraints

Takafumi Koseki　Xuanlang Meng

Dept. EEIS, School of Engineering, The University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656、Japan　(*Email: takafumikoseki@ieee.org*)

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Reducing energy consumption in the transportation sector, particularly in electric railways, is urgently required to realize our sustainable industrial society. Since hardware-based efficiency improvements are nearing physical limits and require high implementation costs, optimizing driving profiles—a software-based approach—offers a highly effective and low-cost alternative. The core of this approach is to maximize the utilization of regenerative braking under strict operational time and speed constraints.

While Dynamic Programming (DP) is conventionally used to calculate optimal trajectories, it faces a severe computational bottleneck known as the "curse of dimensionality," especially when optimizing multiple trains simultaneously. To overcome this, a fast, pattern-based semi-heuristic optimization approaches have been established using the Energy Increment Equalization Method (EIEM) and neighborhood search algorithms.

Crucially, for multi-train coordination, a "receiver-train focused" strategy was introduced to avoid dimensional explosion. Instead of optimizing multiple trains simultaneously, the system optimizes only the re-acceleration timing of the receiving train while keeping the regenerating train's speed profile fixed.

As illustrated in Fig. 1, this strategy enables the efficient transfer of regenerative energy between trains. By actively applying power-limiting braking to avoid the activation of mechanical brakes, the optimal speed profile dynamically adjusts to maximize the absorption of regenerated energy while strictly adhering to schedule constraints.

This theoretical framework was fully validated through commercial field tests on the Fukuoka City Subway. By utilizing Automatic Train Operation (ATO) to perform high-precision control—including jerk regulation and power-limiting braking—the proposed method achieved a total energy consumption reduction of 17.2% with just minor hardware modifications.

Furthermore, this mathematical optimization can be extended to electric vehicles (EVs) which use Dynamic Wireless Power Transfer (DWPT). In the context of DWPT, minimizing infrastructure construction costs requires a contrasting driving strategy: driving as slowly as possible on WPT coils to maximize energy reception, and accelerating in non-charging sections.

The optimal trajectory generation technology under state-variable inequality constraints, successfully implemented in electric railways, transcends its original field. It provides a fundamental framework with significant potential for broader smart mobility systems, including the cooperative control of autonomous EVs and next-generation power infrastructures.

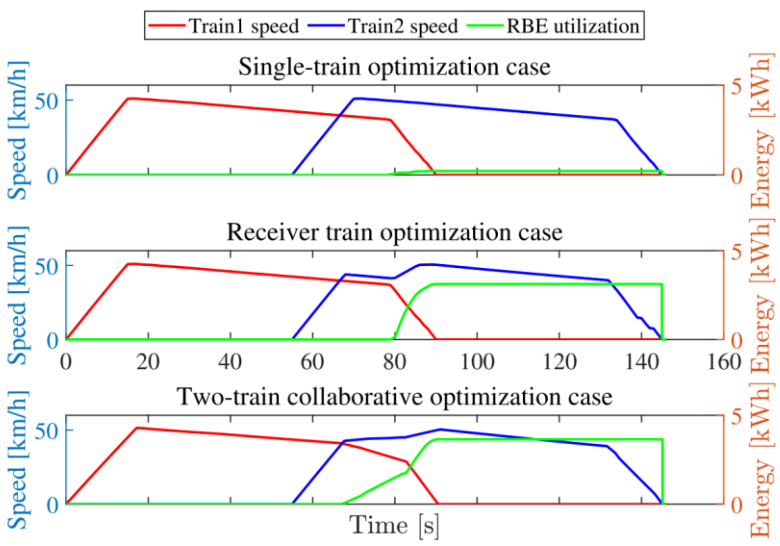

Fig. 1 Case studies for dual energy-saving train operation:
Comparison of train run curves and substation power curves of three optimization scenarios for using regenerated energy with 55s train interval.