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A synergistic energy-efficient planning approach for urban rail transit operations

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ABSTRACT

Large-scale development of urban rail transit has attracted attention owing to its sizable energy consumption. Energy-efficient planning can enhance the distribution and utilization of limited energy resources. This study proposes a two-stage urban rail transit operation planning approach comprising running time allocation and regenerative energy utilization to save energy consumption. The proposed models and algorithms holistically deal with inter-station running time synergy which utilizes surplus running time to achieve minimum energy consumption. They also implement the hauling and braking synergy of multiple trains in multiple trips, with adjustments to departure intervals and dwelling times, to maximize the regenerative energy real-time utilization rate. The algorithms utilize chromosomes in genetic algorithm to represent possible operation stage combinations, conduct feasible direction iterations to facilitate surplus-time effective allocations, and maximize the derived overlap time for operation synergy of trains under the precondition of energy-efficient train movements between stations. A case study of the metro line demonstrates that considerable energy saving is achievable through the proposed planning approach.

1. Introduction

Transportation is one of the major energy-demanding sectors in most energy systems, and modeling for hourly energy consumption distribution benefits energy demand planning [1]. The use of electric energy by transport vehicles can take full advantage of renewable energy consumption, and reduce fossil fuel dependence and environmentally harmful emissions [2]. Renewable energy utilization has also other advantages besides energy output and environment protection, for example, increasing water availability through desalination technology combined with pump storage to generate electricity [3]. More and more electric power systems are penetrated with the utilization of renewable energy resources such as water, solar, wind and hydrogen, for which optimization models can effectively support energy planning [4]. Energy optimization and planning models are required to enhance renewable energy utilization, and facilitate social sustainability development [5].

In China, expansion in transportation is responsible for traffic congestion and environment deterioration [6]. High-speed railways, urban rail transit (URT) and electric vehicles are advanced measures to relieve traffic congestion, decrease oil dependence, and improve energy use efficiency [7]. The URT is undergoing accelerated development in China, with 134 URT lines in over 30 cities covering 4152.8 km in 2016. Rapid urbanization is leading to expansion of cities and URT development is urgency. The construction scale will triple by 2020 with operation over an estimated length of 13385 km [8].

URT consumes huge amount of electric energy, with consumption increasing from 0.65 to 1.39 billion kW•h in Beijing from 2008 to 2015. The total electric energy consumed by URT exceeds 10 billion kW•h annually and accounts for about 50% of the URT operating cost [8]. The measures to save energy can decrease energy demand loads on smart energy grid systems which require broader control and management [9]. As capital investment in the transportation sector increases, implementing energy-saving techniques to elevate productivity becomes paramount [10]. Braking energy storage is reported as a means for considerable energy saving. Modeling of train movements and a flywheel energy-storage system for light rail transit (LRT), resulted in a

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proposed model for energy consumption and costs [11]. The development of a superconducting feeder cable system can save energy for the next-generation rail transit through improved regeneration efficiency, decreased power loss, and balanced power loads [12]. These are the improvements of hardware equipment to save energy for URT. To ensure better usage of limited electric energy, this paper dwells on a holistic synergistic energy-efficient planning approach to handle URT economic operations.

The Pontryagin maximum principle and constraint optimization approach enabled exploration of the train energy-efficient operation problem under definite operation time, operation distance and speed constraints. An alternative switching mechanism involves traction, speed holding (cruising), coasting, and braking [13]. Cheng and Howlett [14] derived critical velocities and utilized them to improve energy efficiency. Khmelnitsky [15] presented an energy-efficient solution approach combining state and joint equations. Liu and Golovitcher [16] advanced an iterative analytical solution algorithm for energy-efficient train operations. Albrecht et al. [17] presented optimal control strategies with speed limits for train movements, proved the existence and uniqueness of optimal solutions. Albrecht et al. [18] revealed the relationships between state and adjoint variables for energy-efficient train movements. Albrecht et al. [19] derived the integral forms of conditions necessary for optimal switching, and developed computational techniques. Determination of switching points resulted from optimization algorithms such as genetic and heuristic algorithms, centered on the switching mechanism. Chang and Sim [20] utilized genetic algorithms to optimize rapid transit of a train considering punctuality, comfort and energy consumption. Wong and Ho [21] employed heuristic measures to find coasting points integrated with a train simulator under the condition of specified inter-station running times. Ke and Chen [22] proposed a heuristic algorithm to optimize train speeds considering energy saving for each signaling block. Bochamikov et al. [23] used genetic algorithms to explore the tradeoff between reduction in energy consumption and increase in running time for a single-train journey. Açıkbaş and Sőylemez [24] used neural networks to estimate energy consumption and optimize coasting points. Feng et al. [25] explored the quantitative relationships between maximum operation speeds and station spacing in view of energy saving using computer simulation. Lin and Sheu [26] proposed an optimization model based on adaptive optimal control for maintaining headway and energy saving, and solved problem using the reinforcement learning solution algorithm. Ke et al. [27] employed the max-min ant system algorithm for train driving optimization. Sheu and Lin [28] proposed an energy-saving approach using dual heuristic programming to optimize coasting points and station dwelling times. Yang et al. [29] optimized energy consumption and travel time using genetic algorithms to solve coasting points. Ning et al. [30] put up a control model integrating headway adjustment with energy saving using the recursive solution algorithm. Albrecht et al. [31] proposed an energy-efficient train control model and algorithm for keeping safe distances between trains. Scheepmaker and Goverde [32] incorporated energy-efficient control into the schedule generation to optimize cruising speeds and coasting points. Lu et al. [33] employed a mixed-integer linear programming algorithm to handle train speed trajectory optimization problems subjective to distance and time constraints. Huang et al. [34] presented an energy-efficient train control framework with a solution algorithm that integrates off-line decision tree-based sequence mining and machine learning with on-line onboard optimization techniques. Carvajal-Carreño et al. [35] developed a fuzzy tracking algorithm to maintain an appropriate distance between a train and subsequent train with energy reduction. Haahr et al. [36] presented a dynamic programming approach to optimize train speed profiles and reduce energy consumption. Canca and Zarzo [37] proposed a mixed integer non-linear optimization model to generate energy-efficient schedules. Ye and Liu [38] proposed nonlinear programming methods for train traction, speed-holding, coasting and braking control. Zhao et al. [39] performed the field test of optimal train trajectory implementation, resulting in significant reduction in energy consumption.

Utilization of energy from regenerative braking of transport vehicles is increasingly gaining attention for energy saving. Adinolfi et al. [40] explored the energy-saving effectiveness of regenerative braking in a subway line. Li and Lo [41] proposed a speed control approach to synchronize the acceleration and braking processes to facilitate the use of regenerative energy. Yang et al. [42] developed an integer-programming model for scheduling metro trains, incorporating regenerative energy into objective functions. Gupta et al. [43] put forward a linear programming model for utilization of regenerative energy by approximating power graphs into rectangles, aligning the midpoints of base sides of the rectangles and selecting the closest train pairs. Yin et al. [44] established an energy-efficient rescheduling model under uncertain passenger demands using approximate dynamic programming with an objective function represented as the difference between tractive energy and regenerative energy. Huang et al. [45] proposed a multi-objective optimization model considering trip time and energy consumption which involves regenerative energy.

Many studies focus on the energy-efficient movement of trains given definite operation time, operation distance and speed limits, but some deal with the utilization of energy from regenerative braking. These two aspects, although closely linked, has only scantily been addressed in a unified way; that is, to establish an energy-efficient planning approach for operation synergies among multiple stations and multiple trains. A problem in optimizing energy consumption associated with train movements is under definite operation time. However, optimum inter-station operation times along an urban rail line should be determined at first for energy-efficient train movements between stations. Another problem is selecting the best departure intervals and dwelling times to maximize the real-time utilization of regenerative energy. The precondition for the selection is that train movements between stations are energy-efficient and result in operation synergy for multiple trains in multiple trips. The estimation of the regenerative energy is incorporated into the energy consumption objective function under the presumption that all the regenerative energy can be stored or utilized, except its conversion loss. However, for the real-time utilization case of regenerative energy, concrete hauling (including traction and cruising stages) and braking synergy among multiple trains located in the same power supply zone should be accounted. Due to energy-efficient operation time constraints, one hundred percent hauling and braking overlaps are practically infeasible. The main contribution of this paper is to establish the link between the operation synergies of the two aspects and formulate a holistic energy-efficient train operation planning approach. It addresses a way to maximize the overlap time by deriving overlap time calculation formulae. The proposed approach involves distributing the running times among inter-stations to minimize the total energy consumption along a URT line, and then, optimizing departure intervals and dwelling times to increase the utilization rate of regenerative braking energy.

Section 2 of this paper deals with the energy-efficient planning approach for URT operations. Section 3 examines the inter-stations running time allocation, while Section 4 explores the utilization of regenerative energy for multiple trains. The efficiency of the proposed energy-efficient planning approach is demonstrated through a case study in Section 5 and the paper ends with conclusions in Section 6.