Simulation Modelling Practice and Theory 84 (2018) 50–68

Contents lists available at ScienceDirect

Simulation Modelling Practice and Theory

journal homepage: www.elsevier.com/locate/simpat

Real time eco-driving of high speed trains by simulation-based dynamic multi-objective optimization

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ARTICLE INFO

Article history:
Received 7 April 2017
Revised 4 December 2017
Accepted 16 January 2018

Keywords:
Simulation
Delay recovery
Dynamic multi-objective optimization
Eco-driving
High speed railway
Real-time traffic operation

ABSTRACT

Eco-driving is a traffic operation measure that may lead to important energy savings in high speed railway systems. Eco-driving optimization has been applied offline in the design of commercial services. However, the benefits of the efficient driving can also be applied on-line in the regulation stage to recover train delays or in general, to adapt the driving to the changing conditions in the line. In this paper the train regulation problem is stated as a dynamic multi-objective optimization model to take advantage in real time of accurate results provided by detailed train simulation. If the simulation model is realistic, the railway operator will be confident on the fulfillment of punctuality requirements. The aim of the optimization model is to find the Pareto front of the possible speed profiles and update it during the train travel. It continuously calculates a set of optimal speed profiles and, when necessary, one of them is used to substitute the nominal driving. The new speed profile is energy efficient under the changing conditions of the problem. The dynamic multi-objective optimization algorithms DNSGA-II and DMOPSO combined with a detailed simulation model are applied to solve this problem. The performance of the dynamic algorithms has been analyzed in a case study using real data from a Spanish high speed line. The results show that dynamic algorithms are faster tracking the Pareto front changes than their static versions. In addition, the chosen algorithms have been compared with the typical delay recovery strategy of drivers showing that DMOPSO provides 7.8% of energy savings.

1. Introduction

High speed railway (HSR) is expanding throughout the world becoming an important energy consumer. It is considered an energy efficient transport mode [32], however, it can be improved and many studies are being carried out to reduce the energy consumption of HSR [34]. These works have the objective of reducing both the economic costs for railway operators and the environmental impact of railways [28,29].

The energy efficiency measures that can be taken in railway systems are usually divided into: measures that involve infrastructure, rolling stock and traffic operation [4,22,71]. Measures related to traffic operation require low investments and the short-midterm actions allow improving the performance of railway systems that are already in operation.

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https://doi.org/10.1016/j.simpat.2018.01.006
1569-190X/

The main energy efficiency actions that can be taken in the field of traffic operation are focused on: traffic design [1,27,35,55,62], on-line traffic regulation [25,42,50,58,59,72], maximization of the use of regenerative energy [21,24,53] and eco-driving.

The work presented in this paper is focused on eco-driving framework. Eco-driving design consists in obtaining the speed profile of a train journey that consumes the lowest amount of energy for a target running time. Eco-driving makes use of the combination of different efficient driving strategies that depend on the type of railway line.

Metropolitan railways are highly automated systems where trains are typically driven by automatic train operation (ATO) equipments. The driving strategies applied in ATO equipped trains are basically: speed regulation [26,51] and coasting-remotoring defined by coasting points [15] or by upper and lower speed limits [6,19,20,37]. Typically, high speed trains are driven manually [69] and the journeys between stations are long-distance travels. The driving strategies applied in HSR are speed regulation [41] and its efficient version, holding speed without braking [40,60,61]. It consists in maintaining a constant speed as long as traction effort is needed. If braking is needed to maintain the speed command, the train will coast increasing its velocity in order to save energy. This command has been tested in Spanish high speed lines and proved to be energy efficient and easily executed by train drivers [60].

Different optimization techniques have been applied in the literature to calculate eco-driving. These techniques are based either on mathematical optimization models or on detailed simulation models.

Mathematical optimization models [3,15,38,45,48,51,54,63] obtain the optimal solution using low computational time. However, the difficulties associated to the analytical resolution of the problem lead to include simplifications in the train, line and driving model. If the speed profile provided by the optimization model is not accurate enough, the solution executed should be recalculated frequently during the journey, even if there are no incidences [38]. Thus, detailed simulation models provide more accurate solutions than mathematical optimization based models and it is possible to easily incorporate to the simulator complex characteristics of the systems (related to the track, train traction/braking or operation), without modifying the optimization algorithm.

In [47], a model was introduced to simulate the dynamic behavior of the train movement. Different algorithms have been applied in combination with a detailed train simulation model in the literature to take advantage of simulation results accuracy [31]: Artificial Neural Networks [2,13], direct search methods [66], Genetic Algorithms (GA) [5,6,9,49,52,60,67,70], multi-population genetic algorithm (MPGA) [39,65], GA combined with fuzzy logic [16,40,61], Differential Evolution [46], Ant Colony Optimization (ACO) [44,52] and Simulated Annealing [68]. These works state the problem as a single-objective optimization.

On the other hand, other works state the problem as a multi-objective optimization problem (MOOP) considering two objectives: energy consumption and running time. To solve the train speed profile optimization as a MOOP, multi-objective searching algorithms have been applied. These methods are Indicator Based Evolutionary Algorithm (IBEA) [12], Non-dominated Sorting Genetic Algorithm II (NSGA-II) [8,20,23] and Multi-Objective Particle Swarm Optimization (MOPSO) [20,30]. These studies make an offline optimization to obtain the Pareto front and then, the railway operator selects the efficient speed profile that the train will execute depending on the commercial running time.

Most of the eco-driving work in the literature is related with the offline planning of railway's efficient driving. However optimal speed profiles can also be obtained in the regulation stage as an on-line calculation. If the train is delayed, the offline eco-driving design is not valid anymore and a new on-line eco-driving calculus is required to recover the delay in an energy efficient way. The challenge of the on-line eco-driving application is the low computation time available to carry out the optimization and the changing situations that may occur along the trip.

Some solutions have been proposed in the literature to solve the on-line eco-driving design. Several works make use of mathematical models taking advantage of their low computation time [15,38,45,51]. However, solutions provided by the previous methods lie in model simplifications and do not take into account comfort restrictions in a long distance travel.

Other works combine GA with simulation [9,67] but solutions provided are not suitable for high speed lines because they demand many coasting-remotoring cycles. In [61], Sicre et al. present a model to calculate in real time a new set of holding speed without braking commands when a delay occurs in a high speed line. This model is stated as a single-objective optimization problem and makes use of a GA with fuzzy parameters.

However, previous models can be improved with the application of Population-based algorithms for dynamic multi-objective optimization problems (DMOOPs) [36]. The use of a dynamic optimization algorithm would permit to reduce the calculation time required for the optimization process, allowing frequent updates of the Pareto front.

The main contribution of this paper is the on-line calculation of the eco-driving of a high speed train by means of a dynamic multi-objective optimization algorithm. The proposed algorithm can be executed in real-time and improves the energy savings provided by static simulation-based eco-driving algorithms, fulfilling the punctuality requirements and taking into account the passenger's comfort**.** The DMOOP regulation algorithm in this paper provides a set of updated and non-dominated solutions that can be used to change the current speed profile as soon as a delay arises or the traffic situation changes. These solutions make use of the holding speed without braking strategy that has been found as the most appropriate manual driving strategy to HSR. Two algorithms are proposed and compared to calculate eco-driving: Dynamic Non-dominated Sorting Genetic Algorithm II (DNSGA-II) [17] and Dynamic Multi-Objective Particle Swarm Optimization algorithm (DMOPSO) [57]. Dynamic algorithms are faster tracking the Pareto front changes than their static versions, providing better energy savings. In addition, the proposed algorithms take into account the passengers' comfort constraints including a