Advances in Engineering Software 000 (2017) 1–13

Contents lists available at ScienceDirect

Advances in Engineering Software

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

Research paper

A stochastic optimization framework for road traffic controls based on evolutionary algorithms and traffic simulation

Junchen Jin[a], Xiaoliang Ma[a,*], Iisakki Kosonen[b]

[a] System Simulation & Control (S2CLab), Department of Transport Science, KTH Royal Institute of Technology, Teknikringen 10, Stockholm 10044, Sweden
[b] Department of Civil and Environmental Engineering, Aalto University, P.O. Box 12100, FI-00076, Finland

ARTICLE INFO

Article history:
Received 18 January 2017
Revised 30 June 2017
Accepted 6 August 2017
Available online xxx

Keywords:
Simulation-based optimization
Archived genetic algorithm
Road traffic controls
Traffic light control
Object-oriented software framework

ABSTRACT

Traffic flow is considered as a stochastic process in road traffic modeling. Computer simulation is a widely used tool to represent traffic system in engineering applications. The increased traffic congestion in urban areas and their impacts require more efficient controls and management. While the effectiveness of control schemes highly depends on accurate traffic model and appropriate control settings, optimization techniques play a central role for determining the control parameters in traffic planning and management applications. However, there is still a lack of research effort on the scientific computing framework for optimizing traffic control and operations and facilitating real planning and management applications. To this end, the present study proposes a model-based optimization framework to integrate essential components for solving road traffic control problems in general. In particular, the framework is based on traffic simulation models, while the solution needs extensive computation during the engineering optimization process. In this work, an advanced genetic algorithm, extended by an external archive for storing globally elite genes, governs the computing framework, and in application it is further enhanced by a sampling approach for initial population and utilizations of adaptive crossover and mutation probabilities. The final algorithm shows superior performance than the ordinary genetic algorithm because of the reduced number of fitness function evaluations in engineering applications. To evaluate the optimization algorithm and validate the whole software framework, this paper illustrates a detailed application for optimization of traffic light controls. The study optimizes a simple road network of two intersections in Stockholm to demonstrate the model-based optimization processes as well as to evaluate the presented algorithm and software performance.

1. Introduction

Nowadays, traffic congestion causes important problems in urban areas including the undermined mobility efficiency and increased fuel consumption and air pollution because of the increasing traffic demand. Road traffic controls are important for mitigating congestion and negative environmental impacts. According to Papageorgiou et al. [22], different traffic control strategies are mainly provided for three areas: urban road networks (e.g. intersection and network traffic light controls), freeway networks (e.g. ramp metering, lane control, and variable speed limit) and route guidance. The effectiveness of traffic control strategies greatly depends on their abilities to react to the live traffic conditions. Therefore, advanced traffic modeling becomes an essential part of the latest traffic control strategies.

While emerging technologies in intelligent transport systems (ITS) have the potential to change the existing infrastructure, there is still a rather long way ahead before they overwhelm the existing ones and become economically more feasible. For road traffic control systems, municipality administrations around the world often apply optimization methods to determine the settings of traffic control measures. In the engineering practice, traffic control parameters are usually pre-tuned according to historical traffic demands. Meanwhile, current policy often requires multiple planning objectives not only for better mobility efficiency, but also for considering more efficient energy usage and environmental sustainability.

As the processes in road transport system are stochastic and nonlinear with many parameters, nature-inspired optimization approaches have been commonly used to solve the optimization problems for traffic control systems. For instance, traffic light control is one of the most widely used traffic control instruments. Moreover, genetic algorithms (GAs), one of the nature-inspired

* Corresponding author.
E-mail address: liang@kth.se (X. Ma).

http://dx.doi.org/10.1016/j.advengsoft.2017.08.005
0965-9978/

optimization techniques, are probably the most frequently used approach for the applications of traffic light optimization [e.g. [26,23,24,19,25]]. Some studies, including the one by Stevanovic et al. [25], have brought utilities for the practice in traffic engineering concerning different aspects including mobility, safety, and environmental impacts. However, the proposed approaches are limited to the dedicated traffic models, and few of them introduce the computational implementations, especially concerning more efficient optimization algorithms and engineering software development.

This study intends to propose a general optimization framework for road traffic controls. The implementation of such a computing framework is due to the engineering requirements in several R&D projects for optimizing traffic lights, lane settings and other measures in collaboration with the Swedish national and municipality transport administrations. A literature review from the aspect of simulation-based optimization for traffic controls is presented in the next section. Whereas the computing framework is introduced in the Section 3, this paper presents more implementation details for a traffic light control application in a later section. A case study is then performed to evaluate the optimization algorithm and demonstrate the capability of the proposed software. Finally, the paper is finalized by summary and perspectives on future research.

2. Literature review

In general, Bierlaire [3] presented the role of simulation in traffic and transportation research, with a focus on simulation-based optimization. When it comes to traffic flows, they can be represented by macroscopic models, or by mesoscopic models, or by microscopic models [2]. Whereas macroscopic simulation model represents traffic flows from an aggregated point of view based on a hydrodynamic analogy, traffic flow is described from the dynamics of the individual particles (the vehicles) in microscopic simulation models. Mesoscopic models, based on a simplification of vehicular dynamics, represent an intermediate alternative for modeling traffic flows.

A large amount of research effort has been put into optimizing traffic controls using aggregated simulation models. For example, Ukkusuri et al. [29] applied a macroscopic simulation model, cell transmission model (CTM), to represent traffic dynamics in a traffic light optimization problem. Liu et al. [16] investigated an optimal variable speed limit (VSL) system capable of optimizing the system designs when the variable message signs (VMSs) are movable using a GA approach. Dell'Orco et al. [7] proposed an artificial bee colony algorithm to find the optimal settings of a traffic light controller in a simulation environment enabled by TRANSYT-7F which integrates a macroscopic simulation model.

Mesoscopic models have been increasingly developed, such as Burghout [4] and Celikoglu and Dell'Orco [5], due to the significant decreases of the efforts involved in traffic modeling compared to microscopic models, and the higher fidelity of traffic system representation than macroscopic models. Nevertheless, previous studies seldom investigated the effects of traffic control systems when traffic flows are mesoscopically modeled. Di Gangi et al. [8] has pioneered a network optimization strategy for traffic light control system based on a mesoscopic traffic flow model. The employed mesoscopic model allows simulating queue and spillback phenomena.

Macroscopic and mesoscopic traffic models usually do not provide sufficient details to characterize the operations of advanced traffic controls or the emerging data where vehicle-level information is required to explicitly model the operations. Over the past decade, different microscopic traffic tools (e.g. VISSIM [9], AIMSUN [1], and SUMO [13]) have been applied for optimization of the traffic control systems when detailed vehicle information is required. For instance, Khondaker and Kattan [12] presented a variable speed limit (VSL) control system in a connected vehicle environment, which focused on individual driver's behavior. A multi-objective optimization function with respect to the control parameters was formulated to find a balanced trade-off among the mobility, safety and environmental benefits. Osorio and Bierlaire [21] proposed a simulation-based optimization framework for solving the traffic light control problems in large-scale urban areas. Their optimization algorithm is based on an analytical approximation of the objective function combining the information from AIMSUN. However, there is a lack of research effort on proposing a general model-based optimization framework that considers the varieties of traffic simulation models and is applicable to the optimization of different traffic control instruments.

The most challenging problem of microscopic simulation-based optimization is the heavy computational burdens since nature-inspired optimization algorithms inherently impose iterative simulations. In each simulation run, detailed states (including position, speed and acceleration) of each vehicle are computed every simulation step. The total computational time can be reduced if traffic simulations are executed in parallel. One example study was conducted by Sánchez-Medina et al. [24] who implemented an optimization framework in the context of using microscopic simulations based on cluster computing. Few studies, however, have focused on the enhancement of the optimization algorithm to reduce the computational load when microscopic traffic simulation models are incorporated.

3. Model-based optimization framework

This section introduces a general computing framework for optimizing traffic control measures. It has three essential elements: the optimization engine, the models of traffic system (including traffic simulator and control measures) and the system performance estimator. We begin with the introduction of the optimization engine.

3.1. GA-based optimization algorithms

While the optimization technique may vary in the proposed framework, the scope of this study only considers GA algorithm, an evolutionary algorithm that has been frequently used in the practice of traffic controls. GA starts with a randomly generated population composed of feasible solutions that evolves through its generations towards the global solution. To create a new generation, GA usually performs *selection, crossover*, and *mutation* operators. Here, parents are described by the strings of bits.

3.1.1. Basic operators

Before the operations, an encoding scheme, often binary encoding, transforms those traffic parameters (often integers) to a string of 0 or 1 before the population is further manipulated. The size of the string is predefined. The lower bound value in decimal corresponds to all zero digits in a bit string, whereas the upper bound value in decimal is represented by all one digits in a bit string. The values between the lower bound and the upper bound are linearly scaled and associated to the corresponding binary strings. Such an encoding of a control parameter ϕ could be analytically represented by

$$\tilde{\phi} = (b_l \dots b_i \dots b_1)_2 = fl\left(\frac{\phi - \phi^{min}}{\phi^{max} - \phi^{min}} \times (2^l - 1)\right) \quad (1)$$

where $\tilde{\phi}$ denotes the signal parameter that is encoded in a bit string, and b_i represents the i^{th} bit in the chromosome; l represents the size of the bit string; $fl(\cdot)$ is the floor function mapping a real