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Modeling the multi-traffic signal-control synchronization: A Markov chains game theory approach

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ABSTRACT

This paper presents a new paradigm for modeling the multi-traffic signal-control synchronization problem using game theory based on the extraproximal method. The objective in a crossing is to minimize the queuing delay and the problem for a signal controller is to find an optimal signal timing strategy, i.e. establishing green timing for each signal phase. Signal controllers are considered the players of the game. Each intersection aims at finding the green time that minimizes its signal and queuing delay. The problem presents natural restrictions: (a) the number of entering cars and exiting cars is different for each street of the intersection and (b) the interval of time given for vehicles to the green light is equal to the red light in the respective opposite direction . The first restriction determines a leader–follower Stackelberg game model: streets having more traffic require more green time. The last restriction establishes a simultaneous-solution of the game as a better consideration of the real situation. Then, to take advantage of the structure of the game, the paper shows that the solution is given by a Nash equilibrium. We introduce the *c*-variable method for finding the optimal signal timing distribution and making the problem computationally tractable. The extraproximal method is a two-step iterated procedure: (a) the first step calculates a preliminary approximation to the equilibrium point, and (b) the second step is designed to find an adjustment of the previous step. The formulation of the game is given in terms of coupled nonlinear programming problems implementing the Lagrange principle. Tikhonov's regularization method is employed to ensure the convergence of the costfunctions to a Nash equilibrium point. In addition, the extraproximal method is developed in terms of Markov chains. The usefulness of the method is demonstrated by a three-way intersection example. The contributions have major implications for real-world applications.

1. Introduction

1.1. Brief review

The number of vehicles increased dramatically worldwide, while building new roadways is no longer a feasible option (specially to old cities) due to the high costs, as well as the fact that the area available for roads has a fixed structure. At peak hours, people waste several hours jammed in traffic. Because population is growing so traffic congestion on roads and the amount of time spent is expected to increase. Therefore, the focus of research is on developing intelligent systems in order to improve transportation congestion problems. The finding of an equilibrium point of both road supply and demand is an analytical dilemma concerning the planning of modern cities having the highest amount of time spent in congestion (Cascetta, 2009; Qu et al., 2012).

The traffic signal control setting is the most important factor that impacts road network efficiency. The problem consists in genarating appropriate signal patterns by controlling the timing of the green/red light cycles at an intersection, with the goal of optimally reducing congestion and the amount of time wasted in traffic (Abdoos et al., 2013; Khamis and Gomaa, 2014; McKenney and White, 2013). This is a very complicated problem by several counts: (1) traffic flows constantly change depending on the times when the most people commute, (2) an intersection influences the traffic flow of other roads (i.e., convergence of several urban blocks), (3) the schools, busy restaurants as well fast food locations where vehicles crowding the entrances are classical causes of traffic congestion, (4) out-of-the-ordinary congestion can be the result of an accident, construction, long holiday weekends, or inclement weather, and (5) additional periods of congestion can be the result of various special events, such as sports events, festivals or religious services, others.

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The focus of the paper is dedicated to solving scenarios corresponding to different demand levels (traffic flows) and different numbers of signalized intersections. The problem presents natural restrictions: (a) the number of entering cars and exiting cars is different for each street of the intersection, (b) there is a traffic conflict in the intersection area between the two movements, therefore they cannot travel at the same time and the traffic signal will be opposite, i.e. when one movement has a green light others movements have a red light. On the one hand, restriction (a) determines a leader–follower Stackelberg game model: streets having more traffic flow require more green light time and can be considered leaders. On the other hand, restriction (b) induces a simultaneous solution of the game as a better consideration of real circumstances, i.e. the interval of time given for vehicles to the green light is equal to the red light at an intersection.

1.2. Related work

In order to minimize delays and to maximize the intersection capacity, many researchers have actively employed different approaches to deal with the signal control setting problem. Allsop (1971, 1976) investigates the relationship between signal setting and traffic assignment, and proposes a two-solutiion program to the traffic equilibrium problem: (1) SIGSET for calculating traffic capacity of signal-controlled road junctions, and (2) SIGCAP for assessing the traffic capacity of signal-controlled road junctions. Gartner et al. (1976) describe a computer method, mixed-integer traffic optimization, designed to optimize simultaneously all the traffic control variables of the network offsets, splits and cycle time. Tan et al. (1979) deal with the signal setting as a hybrid optimization problem. Smith (1979a,b) formulates link-flow definitions of equilibrium and stability, and gives conditions which guarantee the existence, uniqueness and stability of traffic equilibria. As well, Smith (1980, 1981) proposes a traffic control strategy which causes the traffic to be distributed in the spare capacity available on the network requiring only local information such as traffic flows and queue lengths, which can be obtained from vehicle detectors. Chen and Ben-Akiva (1998) present a combined dynamic traffic assignment and dynamic traffic control as a one-level Cournot game and a Stackelberg game. Fisk (1984) described the global optimal signal-setting problem as a Stackelberg game between network users and a traffic agency. Alvarez et al. (2008) and Moya and Poznyak (2009) tackle the signal setting as a noncooperative game problem, as well as using a Stackelberg–Nash game theory approach based on the extraproximal approach (but without intersection restrictions).

Gartner et al. (1980), Gartner and Stamatiadis (1996), Gartner and Al-Malik (1996) present a framework for the integration of dynamic traffic assignment with real-time control, discuss first the static case, involving the interaction between travelers (demand) and transportation facilities and extend the framework to the dynamic case, which involves the incorporation of advanced intelligent transportation systems, combining the model for signal control and route choice in urban traffic networks. Lee and Machemehl (1998) study the signal setting using genetic algorithms. Cascetta et al. (1999) study the combined assignment-intersection control problem and show that it descends from the more general equilibrium network design problem in the case of locally optimized control systems (e.g. adaptive traffic-lights) proposing a Stochastic User Equilibrium (SUE) model with asymmetric delay functions. As well, Cascetta et al. (2006) present models and algorithms for the optimization of signal settings on urban networks proposing: a global approach (optimization of intersection signal settings on the whole network) and a local approach (optimization of signal settings intersection by intersection). Cascetta (2009) presents models and applications related to transportation systems analysis. Qu et al. (2012) develop a traffic control algorithm considering traffic assignment. Dafermos (1980, 1982), Fisk and Nguyen (1982), Florian and Spiess (1982), Gartner (1983), Meneguzzer (Meneguzzer, 1990, 1995), Cantarella et al. (1991) and D'Acierno et al. (2012) deal with the local optimization of signal settings problem as a fixed-point problem, where look for an equilibrium traffic flows congruent with costs and signal settings, and the signal settings are obtained according to a local-optimal control policy. Galloa and D'Aciernob (2013) study the local optimization of signal settings problem that arises when signal control parameters of an urban road network are locally optimized and have to be consistent with equilibrium traffic flows and, compare several solution algorithms proposed in the literature.

Sheffi and Powell (1983), Heydecker and Khoo (1990), Yang and Yagar (1995), Heydecker (1996), Wong and Yang (1997), Wong (1997), Chiou (1999), Wey (2000), Ziyou and Yifan (2002) and Cascetta et al. (2006) tackle the global optimization of signal settings as a (non-linear) constrained optimization problem where signal settings assume the role of decision variables. More recently, Abdoos et al. use an organization called holonic multi-agent system to model a large traffic network. Khamis and Gomaa (2014) focus on multi-objective traffic signal control computing a consistent traffic signal configuration at each junction that optimizes multiple performance indices. Placzek (2014) introduces a self-organizing traffic signal system for an urban road network using an interval microscopic traffic model to predict effects of its possible control actions in a short time horizon.

1.3. Main results

This paper proposes a new modeling approach for multi-traffic signal-control synchronization problem using game theory based on the extraproximal method (Antipin, 2005; Trejo et al., 2015a,b).

- For exploiting the structure of the proposed game, the solution of the Stackelberg game is given by the Nash equilibrium (Clempner and Poznyak, 2011, 2013).
- The extraproximal method is employed for computing the Nash equilibrium of the game. The extraproximal method is a two-step iterated procedure (Trejo et al., 2015a): (a) the first step consists of computing a preliminary position to the equilibrium point, and (b) the second step is an adjustment of the previous prediction.
- The original game formulation is exemplified in terms of coupled nonlinear programming problems implementing the Lagrange principle.
- In addition, Tikhonov's regularization method is employed to ensure the convergence of the cost-functions to a Nash equilibrium point.
- Each equation in this system is an optimization problem, for which the necessary condition of a minimum is solved using the Projector Gradient Method.
- The c-variable method is introduced for finding the optimal signal timing distribution and making the problem computationally tractable. A major advantage of the *c*-variable method is that it can be implemented efficiently for real settings. Moreover, an important aspect of introducing the *c*-variable method is its ability to determine off-normal conditions from information available in the simplex. A non-feasible solution can be detected with a simple test on the *c*-variable.
- The contribution of this work lies in the efficacy and effectiveness of the solution to a real case for designing the signal settings considering the traffic flows and signal-controllers for several intersections.

1.4. Organization of the paper

The paper is organized as follows. The next section presents the preliminaries needed to understand the rest of the paper. Section 3