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On Evaluating Traffic Lights Performance Sensitivity via Hybrid Systems Models

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Abstract

The problem of optimizing traffic light phases dates back to the fifties. Since there, many solutions for different network configurations (isolated intersections, coordinated intersections, and so on) and different modeling and solution approaches (empirical models, queue theory approaches, mathematical programming models, etc.) have been proposed.
In parallel, it has been developed the general theory of hybrid systems, i.e., of those systems characterized by two kinds of states: *normal states* whose variation is governed by a fixed set of equations, and *macro states* whose change is governed by the occurrence of particular conditions or external events.
In this paper, a hybrid model of traffic light dynamics is introduced aiming at providing a modelling framework for evaluating the sensitivity of the performances of different approaches for signal setting optimal design.

Keywords: Signalized intersections; Hybrid Systems; Sensitivity Analysis

1. Introduction

The problem of optimizing traffic light phases dates back to the fifties (Webster, 1958) and, since there, many solutions for different network configurations (isolated intersections, coordinated intersections, and so on) and different solution approaches (empirical models, queue theory approaches, mathematical programming models, etc.) have been proposed.

In this framework, different solutions and strategies (see Papageorgiou *et al.*, 2003, and the reference therein) have been proposed for large scale networks, such as TRANSYT (Robertson, 1969), and SCOOT (Hunt *et al.*, 1982), which were characterized by limited traffic-responsive capabilities, or OPAC (Gartner, 1983), PRODYN (Farges *et al.*, 1983), and RHODES (Mirchandani and Head, 2001) which, on the contrary, implemented traffic-response strategies.

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Nevertheless, in the common practice, the design approaches proposed by Webster (1958), Allsop (1971 and 1976) and (Improta and Cantarella, 1984) for isolated intersections, are still widely used. Despite the clearness and analytical rigorousness of such approaches, they neglect the dynamics of intersection and flows and, in particular, assume the incoming flows to be known and constant for each design reference period.

In parallel, it has been developed the general theory of *hybrid systems*, i.e., of those systems characterized by two kinds of states: *normal states* whose variation is governed by a fixed set of differential equations, and *macro states* whose change is driven by the occurrence of particular conditions or external events (Antsaklis, 1998a and 1998b). For such a class of systems, any macro state transition generally provoke a change of the set of equations that drive the normal state dynamics. Moreover, such systems characterized by two kinds of equilibrium states: those relevant to the normal states and those relevant to the macro states.

In this framework, urban transportation networks and intersections, together with the relevant traffic lights, can be suitably modeled as hybrid systems with macro-states characterized by the different flows, tragic light signals, or even exogenous variables, such as accidents that change the capacity of roads and intersections (Basile et al., 2004; Di Febbraro and Sacco, 2004; Kim et al., 2008; Basile et al., 2012),.

In this paper, a hybrid model of traffic light dynamics is presented with the aim of providing a framework for evaluating the sensitivity of the performances of different common approaches for the optimal signal setting design. In particular, the methodologies for the computation of the optimal signal settings proposed by Allsop (1976) and Improta and Cantarella (1984) are evaluated by (I) determining the optimal signal settings assuming the incoming flows are fixed, and (II) by evaluating the performance of the above methodologies when the incoming flows are considered stochastic variables with given distribution.

To cope with the problem considered in this paper, traffic lights and the relevant queue at the accesses are represented as a hybrid system, being the queues length the normal state variables.

The main result of the paper is a major comprehension of the intersection and traffic light dynamics, with particular attention to the performance sensitivity of different, well-known, traffic light settings optimization approaches.

The results of the proposed analysis can help in forecasting and preventing queue instability at intersections, helping also in designing better traffic light control systems. In addition, the proposed model is sufficiently general to be applied to other design approaches, and to allow the statement of a sensitivity minimization problem, as will be discussed in the end of the paper.

The paper is organized as follows: after briefly recalling some basic aspects of hybrid systems, the proposed model is described. Then, by means of a real world case study consisting of an intersection in the Italian city of Benevento, the sensitivity analysis of the considered design approaches is performed. Finally, some considerations about the definition of a sensitivity minimization problem are provided.

2. Basics on Hybrid Systems

In the last decades, the attention of many researchers has been focused on Hybrid Systems (HSs) that can be thought of as the most general systems gathering ordinary Time Driven Systems (TDSs), and Discrete Event Systems (DESs).

In this framework, on one hand, TDSs are the well-known systems whose state variables assume real numeric values and whose dynamics is described by differential equations. The dynamics of flows along road stretches is a valuable example of TDSs.

On the other hand, DESs can be intuitively defined as *discrete-state event-driven systems* where the evolution of the state variables, which are not necessarily numeric, depends entirely on the occurrence of asynchronous, often stochastically predictable, events. In such a definition, an event can be, informally, thought of as *something instantaneous* whose occurrence causes a transition from a state to another state of the system. In DESs, an event can be identified with a specific action taken (for instance, somebody presses a button), with a spontaneous occurrence dictated by nature (for instance, a computer goes down for whatever reason too difficult to figure out) or, finally, with a result of several conditions which are suddenly all met (for instance, the fluid in a tank exceeds